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INTENSITY RELATIONS IN THE SPECTRA OF TITANIUM-III INTENSITIES IN SUPER-MULTIPLETS OF TI I.

By George R. Harrison

ABSTRACT

Intensity measurements have been made on a complex super-multiplet of normal titanium, $^5D'FG'-{}^5H'GF'DP'$, arising from the transition $[(3d)^24s]\,4p-4d$, parent term a^4F', and on a simple super-multiplet $^5D'FG'-{}^5F'$ arising from the transition $[(3d)^24s]\,4p-5s$. The intensities of the latter have been found to be practically normal, the multiplet ratios being measured as 8.95:7.00:5.30, or within 6% of the theoretical values, with no self-reversal or excitation corrections needed. The complex super-multiplet has extremely anomalous intensities, as might be expected from the fact that it contains strong $^5FH'$ lines and that a number of lines allowed by the selection principles and usually of considerable intensity are found to be entirely missing in its multiplets. Very few lines have normal intensity ratios to one another, and in no individual multiplet is the Sum Rule fulfilled. In the super-multiplet as a whole the fulfillment of the Sum Rule is only slightly better; the average deviation of the sums from the mean is about 15%, after an excitation correction corresponding to 2080°A for the temperature of the emitting arc has been applied. No other temperature will furnish a correction making the deviation appreciably less. Kronig's formulas for the relative intensities of the nine multiplets hold only roughly. The measurements were made rather difficult by the relative weakness of the lines and by the presence of Cyanogen bands in their neighborhood, but results from a number of sets of plates showed very good agreement, and it is believed that the average final error is considerably under 10%.

Theoretical formulas based on the Correspondence Principle have been given by Kronig[1] for the relative intensities of related multiplets, and by Kronig and others[2] for the relative intensities of lines in multiplets. These formulas have been experimentally verified in a sufficient number of cases to indicate their fundamental correctness, but they are not always applicable. When anomalous intensities are observed they

[1] R. de L. Kronig, Zs. für Phys., *33*, p. 261; 1925.

[2] R. de L. Kronig, Zs. für Phys., *31*, p. 885; 1925.
A. Sommerfeld and H. Hönl, Sitz. Preuss. Akad. Wiss., *9*, p. 141; 1925.
H. N. Russell, Proc. Nat. Acad. Sci., *11*, p. 314; 1925.

are not considered to discredit the formulas, but rather to belong to cases where perturbations exist in the atom which render the assumptions made in their derivation invalid. One of the important problems in the study of the spectra of any element is to determine which spectral lines obey the simple formulas and which do not.

None of the older theories gives the intensities of inter-system combination lines, which by them are expressly forbidden. Yet in many complex spectra, particularly where the separations within a multiplet are large compared to those between related multiplets, these lines are quite intense. Ornstein and Burger[3] showed that in a ^3PD multiplet of normal mercury one of the lines was abnormally weak, the missing energy being found in an intercombination line which had to be added in to satisfy the Sum Rule. They showed that a definite intensity relation exists between a triplet multiplet and its related singlet, a result predicted theorectically in the formulas of Kronig. Ornstein and Burger thus indicated that where inter-system combination lines exist in the singlet-triplet case, it is necessary to include their intensities in the application of the Sum Rule, which must be applied to the whole "enlarged multiplet" (*erweiterte multiplett*).

An important paper by Houston[4] has recently appeared, which contains intensity formulas deduced from the new quantum mechanics. While limited to lines arising from terms due to two-electron configurations, one being an *s* electron, the theory indicates the importance of the enlarged multiplet idea, and predicts the intensities of the inter-system lines. It seems certain that definite application of the new quantum principles to the more complex cases will give exact formulas which will predict the relative intensities of all the lines in the spectra, whether normal, or inter-system, or of other so-called forbidden types. The experimental determination of the relative intensities of such lines is in any case of great importance.

Russell[5] and others have noted that certain related groups of multiplets seem to bear qualitative intensity ratios to one another which suggest the intensity ratios of lines in multiplets. He referred to these as "super-multiplets." Kronig's formulas enable us to calculate the exact theoretical ratios of the total intensities of such multiplets, and the super-multiplet is shown to be a very real thing. The triad groups measured in the second paper of this series are simple types of

[3] L. S. Ornstein and H. C. Burger, Zs. für Phys., *46*, p. 303; 1926.
[4] W. V. Houston, Phys. Rev., *33*, p. 297; 1929.
[5] H. N. Russell and W. F. Meggers, Sci. Paper Bur. Stds., No. *558*; and elsewhere.

super-multiplet; the present paper deals in part with a more complex type.

It seems reasonable to expect that when inter-combination lines and multiplets of types forbidden by the simple correspondence principle formulas exist, they must be added in with certain groups of related multiplets to form an "enlarged super-multiplet" before the Sum Rule can be applied. Their existence in any particular spectrum in appreciable strength would then lead one to expect abnormal intensities in the multiplets included in the enlarged super-multiplet.

It is convenient to list some of the degrees of anomaly which may be expected to characterize line intensities as follows:

1. The Sum Rule and the intensity formulas are obeyed in each multiplet.

2. The Sum Rule is obeyed in each multiplet, but the line intensities are individually anomalous.

3. The Sum Rule is not obeyed in each multiplet, but is obeyed when two related multiplets of different systems and their inter-combination lines are added together, their intensities (in the singlet-triplet case) being given by Houston's formulas.

4. The Sum Rule is obeyed for this enlarged multiplet, but the individual intensities are anomalous.

5. The Sum Rule is obeyed only when a number of related multiplets are added together in a super-multiplet.

6. The Sum Rule is obeyed only when two related super-multiplets of different systems and their inter-combination multiplets are taken together to form an enlarged super-multiplet.

Higher degrees of anomaly undoubtedly exist, but neither experiment nor theory furnish any data on them at present. It seems probable that the Sum Rule can be expected to generally hold in the limiting case where all the lines corresponding to a given electron transition are included. In the intensity measurements described below some of these different degrees of complexity of application of the Sum Rule are made use of as standards of reference.

SUPER-MULTIPLETS IN NORMAL TITANIUM

A somewhat typical complex super-multiplet exists in the spectrum of Ti I, originating from the transition $[(3d)^2 4s]\ 4p - 4d$. The addition of the p electron to the common parent term a^4F' gives rise in part to a triad $^5D'FG'$, while the addition of the d electron in its place produces a pentad, $^5H'GF'DP'$. Combinations between these various terms

give rise to 84 lines which have been observed, four being $^5FH'$ lines of comparatively great strength. Twenty-seven additional lines predicted by theory have not been observed. Table 1, (a), gives King's estimate, as given by Russell[6], of the intensity of the strongest line in each multiplet, which may be taken as a rough indication of the whole multiplet intensity. In (b) are given the theoretical intensities of the multiplets as computed from Kronig's formulas. It is interesting to note that the multiplets in this super-multiplet bear the same theoretical ratios as the lines in a ^7PD multiplet. Comparison of (a) and (b) shows that the qualitative intensities in the super-multiplet agree roughly with those predicted, with the exception of the $^5FH'$ combination. This indicates the probable presence of perturbations, and taken together with King's estimates of the intensities of many of the individual lines, as given in the tables below, leads us to expect anomalous intensities in this super-multiplet.

TABLE 1

	(a)			(b)		
	a^5G'	a^5F	a^5D'	a^5G'	a^5F	a^5D'
a^5H'	30	12	x	264	0	x
a^5G	15	25	x	81	135	x
a^5F'	2	5	7	15	105	48
b^5D	x	10	8	x	40	80
b^5P'	x	x	10	x	x	72

Unfortunately, although it is the strongest complex super-multiplet of Ti I, most of the lines in this group are comparatively weak and the difficulties of measurement are greater than usual. A further source of error is produced by the presence of the Cyanogen bands in the region occupied by several of the more important multiplets. The results obtained from a number of plates show very good agreement, however, and it is believed that experimental errors have been eliminated to a much greater degree than was thought possible at the start of the work.

EXPERIMENTAL INVESTIGATION OF INTENSITIES

The spectral range covered by the complex super-multiplet under discussion is 4280-3681A. As soon as it was found from preliminary measurements that the line intensities were highly anomalous it was deemed advisable to study simultaneously a group of lines of similarly weak but normal intensities, in order to make sure that the abnormal-

[6] H. N. Russell, Astrophys. Jour., *66*, p. 347; 1927.

ities were not due to errors in measurement. A simple type super-multiplet in the visible which has not previously been worked on was chosen and found to be quite suitable. The intensities found for this group of about 30 lines will be discussed later in the paper. They show how far the accuracy of the intensity measurements can probably be trusted, and give important information about self-reversal.

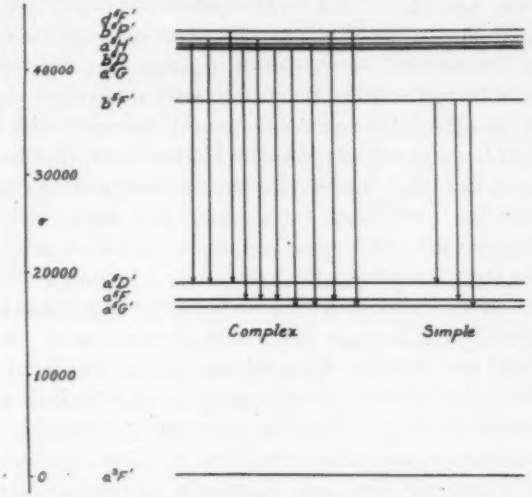

FIG. 1. *Energy level diagram, showing the relative levels of the stationary states involved in the complex and simple super-multiplets measured, with reference to the lowest level of the normal titanium atom. Each horizontal line represents five (or in two cases three) sub-levels.*

The complex super-multiplet was photographed on Eastman 36 plates held in four cassettes in the second order of the 10 meter concave grating, dispersion 0.74 A. mm, while the simple one was simultaneously photographed on Wratten Panchromatic Plates held in two cassettes placed in the first order, dispersion 1.61 A. mm. The density range of lines in the two super-multiplets was found under these conditions to be approximately the same, the panchromatic plates being less sensitive than the others by about the same ratio that the first order was brighter than the second. It was thus possible to photograph both together with the same time of exposure and excitation conditions.

A low pressure arc of the type previously described was used as a source, but it was found that the Cyanogen bands appeared with great intensity at all pressures below 25 cm Hg. Accordingly all measurements were made at pressures of 30 cm or above. This has the dis-

advantage of increasing self-reversal, but fortunately the lower terms involved lie comparatively high in the atom, and this was found to be practically negligible. Fig. 1 shows an energy level diagram giving the relations between the terms involved.

The relatively high pressures used greatly increased the brightness of the arc, and exposures of 50 seconds were sufficient to bring out even the weakest lines. Currents of 1.5 to 3.0 amperes were used; under these conditions the strong lines of the spectrum were given normal exposures in a few seconds, so that most of them were much too strong to measure on these photographs. It is estimated that the average intensity of the lines measured in the present case was in the neighborhood of 2 % of those previously measured in titanium. Several long exposures were taken while hunting for the lines allowed by the selection principles but not previously found; none was discovered, however.

The chief source of error in measuring such weak lines lies in the magnitude of the irregular background correction. Fortunately as the slit width is decreased down to a certain limit the background decreases in intensity while the lines do not. Most of the lines in the complex super-multiplet are listed by King as nebulous in the electric furnace. In the low pressure arc they were found extremely narrow and sharp, so that it was possible to decrease the slit width considerably. This cut down the background correction, but even so, in the weakest lines the background was often over half as strong as the line itself. This reduces the accuracy of the photometry considerably, especially where bands and numerous other lines occur as in titanium, and where such a wide spectral range must be covered.

Six sets of plates, each containing 10 exposures to the titanium spectrum, with the necessary calibration and standardization exposures, were taken. From these from twenty to forty sets of values were found for the intensities of the various multiplet lines, and the values given below represent averages of this number of determinations. The weaker lines, listed as 3 or below in King's estimates, varied somewhat from one spectrum to another, but the stronger ones showed surprising constancy in their relative values, although their absolute values were varied over a wide range.

Calibration was carried out in the manner previously described, a straight ribbon filament tungsten lamp being used as a source. Two similar lamps were used as energy distribution standards, their brightness temperatures being measured with a Leeds & Northrup optical pyrometer, and also with a similar Siemans & Halske instrument.

The temperatures measured by the two agreed within the accuracy of reading, which was about three degrees. The color temperatures were obtained from the brightness temperatures using Zwikker's data,[7] curves having been drawn which gave color temperature directly in terms of pyrometer milliameter readings.

In order to determine the magnitude of the temperature error produced by the loss of light at the glass envelope of the lamp bulb, the temperature of one lamp was measured with and without the bulb of the other lamp interposed in the pyrometer beam. The positions of the lamps were then reversed, and a number of such readings indicated that a single thickness of glass on one lamp produced an error of about 40°C at 2500°, while with the other the error was slightly less. The necessary corrections were then applied to all observed temperatures for the two lamps.

As the lamps were to be used as energy distribution standards between 5800A and 3680A, it was necessary to apply a correction for the varying transmission of the glass with wave length. Its transmission factors for various wave lengths in this range were determined directly with a spectro-radiometer, and were found to vary (for a single thickness of glass) from 94% at 5700A to 80% at 3600A for one lamp, and from 88% to 76% for the other, which was slightly more coated on its inner surface with tungsten. Thus if this correction had been neglected, errors in the energy distribution curves of about 15% would have resulted. The spectral changes in emissivity of tungsten below 4000A produce errors in the opposite direction, however.

Both lamps were used for standardization of the plates, and exposures to each were taken at three or four different temperatures. Each plate thus contained at least six separate sets of standardization exposures to relate it to the other plates of its set. These, together with the four individual calibration curves which could be plotted for each wave length, greatly increased the accuracy of the measurements.

As a further check on the energy distribution curves of the lamps, they were compared photographically in a prism spectrograph with the energy distribution of the light from a slit in the center of a one-fourth inch graphite rod, placed in vacuum and operated at temperatures between 2200°A and 2900°A by currents up to 300 amperes.

In Table 2 are listed all the lines so far found in the complex super-

[7] H. B. Dorgelo, Phys. Zeits., *26*, p. 756; 1925.

multiplet, together with certain inter-combination lines related to it in a manner described below. The lines are arranged in the order of wave length in a given multiplet, with an arbitrary letter given each line for purposes of identification in the tables that follow. The multiplet designations, wave lengths, and term assignments are as given by Russell.[6] The column marked "Remarks" contains symbols that indicate corrections that had to be applied. *G* indicates that the line was lapped by the ghost of a neighboring line, while the number following it gives the approximate percentage correction that was applied on this account. *E* indicates that another line of unknown intensity was lapped close enough to the line to make accurate intensity determinations impossible, but that estimates of intensity could still be made. *L* indicates that another line was lapped on the desired line, the two never having been resolved, so that even an intensity estimate was impossible. The symbol of a chemical element indicates that one of the lines listed in Kayser's *Tabelle der Hauptlinien der Linienspectra* lies at the same wave length, and might be lapped on the line if that element were present in the source. While the titanium metal used was especially pure, a few of the stronger vanadium lines were observed, and very small traces of other elements might be present. Glass filters were used in certain of the cassettes to prevent overlapping of spectra of other orders on the plates.

The fifth column of Table 2 gives King's (or when in parentheses, Russell's) estimates of the relative intensities of the lines, often very useful for discovering unknown laps and for other purposes. Column 6 gives the theoretical line intensity (amplitude squared) of each line in the super-multiplet, calculated on the same basis for the whole group, while Column 7 gives the measured value relative to certain lines in Multiplet 254 taken as normal, divided by ν^4 to put the two columns on the same basis.

It is misleading to attempt to make direct comparisons between the computed and measured lines of Table 2 because of the presence of an unknown excitation correction. We can compare the lines in the individual multiplets neglecting this, however, since the line separations are in this case small. For this purpose it is desirable to reduce the intensities in each multiplet to a new basis so as to make direct comparison easier.

As many of the intensities are obviously anomalous, it is desirable to see if any group of lines of normal relative intensities exists. This can be most readily done by plotting the common logarithms of the meas-

TABLE 2.

Line	Wave-length	Lower state	Upper state	King's estimate	I/ν^4 theoretical	I/ν^4 Measured	Remarks
214–a	4280.08	$a^5D'_4$	$-b^5D_3$	$2n$	48	28	
b	4278.81	3	2	$3n$	64	58	V
c	4276.66	2	1	2	56	34	L?
d	4274.41	1	0	$(1n)$	32	15	E
e	4268.92	1	1	$(1n)$	8	12	G 20
f	4266.21	2	2	$3n$	40	59	
g	4265.28	0	1	$3n$	32	47	
h	4261.61	3	3	$5n$	112	116	
i	4258.53	1	2	$4n$	56	78	
j	4256.04	4	4	$8n$	240	177	
k	4249.13	2	3	$5n$	64	65	
l	4237.79	3	4	(2)	48	30	E
212–a	4273.31	$a^5D'_3$	$-e^5F'_2$	2	0	36	
b	4270.14	4	4	$7n$	0	94	
c	4260.74	2	3	2	0	29	Fe
d	4251.76	3	4	$2n$	0	33	L
226–p	4150.54	$a^5D'_2$	$-b^5P'_1$	3	50	37	
q	4143.28	1	1	3	65	43	Fe
r	4143.04	3	2	$7n$	134	93	
s	4139.83	0	1	2	29	15	
t	4137.29	4	3	$10n$	260	131	
u	4131.26	2	2	4	84	40	Mn
v	4124.00	1	2	$(1n)$	21	11	
w	4120.01	3	3	2	67	21	Fe, Mo
234–a	4074.36	$a^5D'_4$	$-d^5F'_4$	3	21	15	G 12
b	4071.48	3	3	2	29	22	
c	4071.26	2	2	2	27	19	
d	4068.65	0	1	(1)	19	8	G 30
e	4058.15	4	5	7	151	78	
f	4057.64	3	4	5	103	58	G 20
237–g	4049.39	a^5F_5	$-a^5G_5$	$2n$	33	18	
h	4040.33	4	4	$4n$	48	30	
i	4031.77	3	3	$3n$	47	33	
j	4030.53	5	6	$25n$	390	274	
k	4026.54	4	5	$25n$	297	233	
l	4021.87	3	4	$25n$	220	195	G 8 Fe
m	4017.78	2	3	$15n$	161	137	
n	4015.40	1	2	$12n$	116	116	G 3
240–d	4016.30	a^5F_5	$-e^5F'_4$	6	0	39	G 12
g	4012.81	4	3	3	0	20	
b	3994.70	3	3	$4n$	0	<44	L
p	3993.79	4	4	1	0	10	
241–o	4013.60	a^5F_5	$-a^5H'_6$	$12n$	0	134	G 1
p	4008.07	4	5	$9n$	0	85	
q	4007.21	2	3	$3n$	0	25	
r	4005.98	3	4	$6n$	0	48	

TABLE 2. (Continued)

Line	Wave length	Lower state	Upper state	King's estimate	I/ν^4 Theoretical	I/ν^4 Measured	Remarks
244–s	4003.80	a^5F_5	$-b^5D_4$	$10n$	125	90	
t	4002.50	4	3	$9n$	85	82	
u	3999.34	3	2	$7n$	55	74	Lc
v	3994.70	2	1	$4n$	32	<44	L
w	3990.18	1	0	$(1n)$	16	13	E
x	3984.33	3	3	3	24	25	E
y	3981.47	4	4	$(1n)$	17	20	Zr
253–a	3912.58	$a^5G'_5$	$-a^5G_4$	(2)	23	13	
c	3911.18	6	6	$8n$	218	68	E
d	3899.67	5	5	(2)	160	<62	L
f	3897.32	4	3	1	22	13	
h	3888.04	4	4	$4n$	117	41	
j	3884.04	3	2	(2)	15	14	G 15
m	3882.13	5	6	$15n$	16	205	
n	3877.60	3	3	$2n$	88	44	
o	3875.29	4	5	$20n$	23	<287	L
q	3869.32	2	2	$5n$	75	106	
r	3868.42	3	4	$10n$	22	210	
u	3862.84	2	3	$10n$	15	117	
254–b	3911.37	$a^5G'_6$	$-a^5H'_5$	(2)	1	12	E
e	3897.58	5	4	1	2	13	
g	3895.24	6	6	$30n$	42	220	
i	3887.33	4	3	$(1n)$	2	9	G 5
k	3882.87	6	7	$20n$	720	700	
l	3882.34	5	5	$10n$	61	182	
p	3873.25	4	4	$10n$	61	146	Co
s	3867.77	3	3	3	41	74	
t	3866.45	5	6	$15n$	582	262	
v	3858.12	4	5	$15n$	466	208	Ni
w	3853.74	3	4	$10n$	369	172	
x	3853.05	2	3	$10n$	294	133	
258–a	3842.61	a^5F_5	$-a^5F'_4$	(3)	33	18	
b	3828.17	5	5	3	297	54	G 5
c	3827.48	3	2	1	45	14	
d	3822.03	4	4	(2)	190	46	G 2
e	3821.74	2	1	2	30	30	G 4
f	3817.65	3	3	5	118	47	
g	3814.86	2	2	4	75	32	
h	3813.26	1	1	(0)	60	6	
i	3807.78	4	5	1	33	14	L
j	3806.45	1	2	1	30	10	
k	3805.48	3	4	1	47	12	
l	3805.13	2	3	1	45	13	
278–m	3720.38	$a^5G'_6$	$-a^5F'_5$	2	43	18	
n	3707.53	5	4	$10n$	33	33	G 20
o	3696.88	4	3	2	25	10	G 20
p	3681.23	2	1	1	13	5	G 6

ured intensities against those of the computed intensities, when lines having the proper relative intensities will lie on 45° lines unless self-reversal is present. This has been done in Fig. 2.

This figure, which contains points corresponding to most of the lines except the weaker ones, indicates at once that no completely normal multiplets exist, but that there are a few groups of two, three, and four lines in certain multiplets which have the computed ratios. This, however, is not sufficient to prove the non-existence of self-reversal,

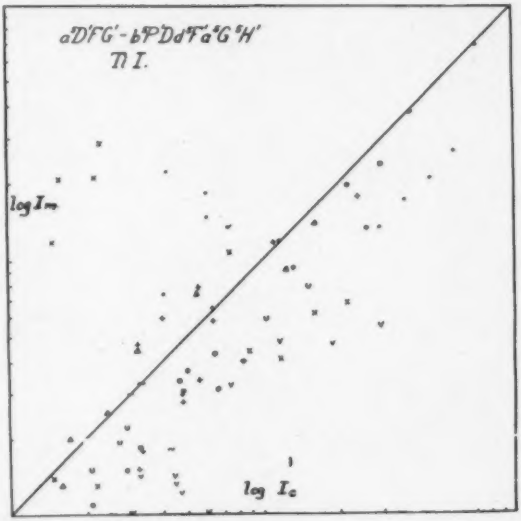

FIG. 2. *Plot showing the common logarithms of the measured intensities of the lines in the complex super-multiplet plotted against the logarithms of their intensities calculated from the simple intensity formulas. Those lines which are normal relative to one another in a given multiplet lie on lines inclined at 45° to the axes.*

and we turn for the moment to a consideration of the simple super-multiplet which was measured at the same time.

The data for this triad super-multiplet are given in Table 3, while the corresponding log I_c − log I_m plot is given in Fig. 3. Here we are obviously dealing with a practically normal set of multiplets, and the self-reversal is negligible. These multiplets have the same lower states as do those of the complex super-multiplet, and as they are fundamentally stronger than the latter, we are justified in assuming less self-reversal for the complex than for the simple super-multiplet. This seems to point conclusively to the absence of self-reversal in the former.

The dashes in Table 3 correspond to weak lines that could not be measured due to underlying bands or to other sources of error. If we

TABLE 3

Line	Wave length	Lower state	Upper state	King's estimate	I/ν^4 Theoretical	I/ν^4 Measured
81–a	5720.49	a^5D_1'	$-b^5F_1'$	3	20	—
b	5716.48	2	2	4	29	—
c	5713.93	0	1	3	20	25
d	5711.94	3	3	4	30	59*
e	5708.27	4	4	3	21	28
f	5702.69	1	2	6	40	39
g	5689.47	2	3	10	68	64
h	5675.41	3	4	9	107	98
i	5662.16	4	5	12	157	160
Sum					‡500	‡530
109–a	5263.50	a^5F_5	$-b^5F_4'$	3	22	—
b	5255.82	4	3	5	31	28
c	5247.30	3	2	5	30	27
d	5238.58	2	1	6 lap	20	39-lap
e	5224.96	4	4	8	127	118
f	5224.57	3	3	6	79	80†
g	5224.32	5	5	15	198	193
h	5223.64	2	2	6	50	43
i	5222.68	1	1	6	40	39
j	5207.87	1	2	3	20	16
k	5201.12	2	3	4	30	27
l	5194.04	3	4	4	31	45
m	5186.32	4	5	3	22	23
Sum					700	700
130–a	5025.58	a^5G_6'	$-b^5F_5'$	18	260	260
b	5013.30	5	4	18	198	202
c	5001.01	4	3	10	147	145
d	4989.16	3	2	10	107	104
e	4978.21	2	1	10	77	75
f	4977.75	5	5	5	22	26
g	4973.06	4	4	6	32	31
h	4968.57	3	3	6	31	28
i	4964.75	2	2	5	21	19
Sum					‡900	‡895

* Probable lap.

† Value uncertain because of close neighboring lines.

‡ Second order satellites, not listed or measured, are included in these sums at their computed values.

give these their theoretical intensities, tentatively, we find the ratios of the total intensities of the three multiplets to be 8.95:7.00:5.30.

This is in satisfactory agreement with the theoretical ratios 9:7:5, the maximum difference being 6%, which is probably somewhat less than the experimental error where the lines are so weak relative to the background. King's estimates for the lines not measured indicate that they are probably normal, or if not, do not deviate much from the theoretical values. The deviations of the measured lines may not be real; it can be seen from Fig. 3 that the deviation increases for the weaker lines, indicating that it is probably due to experimental error. No excitation correction is needed for this super-multiplet, as all three

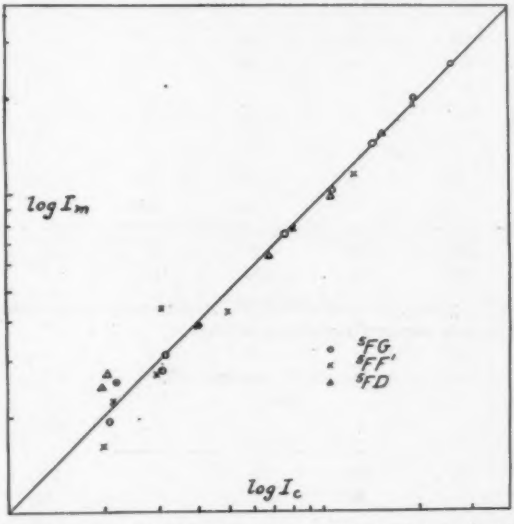

FIG. 3. *Plot similar to Fig. 2, but for the lines of the simple super-multiplet.*

multiplets come from the same upper state, and the separations of the individual terms in this are small. The intervals in the terms involved in these multiplets are practically all normal.

Returning to the consideration of the complex super-multiplet, we proceed to the examination of its individual multiplets. These are listed in the following tables, arranged to show the departures from the Sum Rule. The upper number in each case gives the theoretical intensity of the line in the multiplet, while the lower one indicates the measured value.

Where the lines are so abnormal it is a question as to which line should best be given the normal value as a basis for comparison.

The method used was to select the largest group of lines having mutually normal ratios and call them normal.

TABLE 4. *Multiplet 214.*

	b^2D 4		3		2		1		0	Sum
4	*j* 180	*a*	36		x		x		x	216
	90		14							104
3	*l* 36	*h*	84	*b*	48		x		x	168
	15*e*		59		30					104
$a^5D'2$	x	*k*	48	*f*	30	*c*	42		x	120
			33		30		17			80
1	x		x	*i*	42	*e*	6	*d*	24	72
					40		6		8	54
0	x		x		x	*g*	24		x	24
							24			24
Sum	216		158		120		72		24	
	105		106		100		47		8	

Notes: Lines *f*, *i*, *e*, and *g* taken as normal (all others proportionately weaker). Multiplet is characterized by some degree of asymmetry in satellites.

TABLE 5. *Multiplet 225.*

	b^2P' 3		2		1	Sum
4	*t* 108		x		x	108
	80					80
3	*w* 28	*r*	56		x	84
	13		56			69
a^5D' 2	*z* 4	*u*	35	*p*	21	60
	—		24		22	46
1	x	*v*	9	*q*	27	36
			7		26	33
0	x		x	*s*	12	12
					9	9
	140		100		60	
Sum	97		87		57	

Notes: Lines *p*, *q*, and *r* taken as normal. All others relatively weaker. Lines *s*, *t*, *u*, and *v* normal relative to one another.

TABLE 6. *Multiplet 234.*

	d^5F' 5	4	3	2	1	Sum
4	*e* 220	*a* 30	2	x	x	252
	166	30	—	—		196
3	x	*f* 150	*b* 42	4	x	196
		116	44			164
a^5D' 2	x	x	*g* 96	*c* 40	4	140
			0	38	—	42
1	x	x	x	*h* 56	*i* 28	84
				0	0	0
0	x	x	x	x	*d* 28	28
					16	16
Sum	220	180	140	100	60	
	166	146	46	42	20	

Notes: Lines *a*, *b*, and *c* taken as normal. All others relatively weaker. Three relatively strong lines not found (intensities marked 0).

TABLE 7. *Multiplet 237.*

	a^5G 6	5	4	3	2	Sum
5	*j* 546	*g* 46	1.8	x	x	594
	540	36	—			576
4	x	*k* 416	*h* 67	3.4	x	487
		465	60	—		525
a^5F 3	x	x	*l* 309	*i* 66	3.0	378
			390	66	—	456
2	x	x	x	*m* 225	*o* 45	270
				274	0	274
1	x	x	x	x	*n* 162	162
					232	232
Sum	546	462	378	295	200	
	540	501	450	340	232	

Notes: No two lines except *j* and *i* have normal ratios. The principal lines in this multiplet were measured in Paper I and listed as normal. This error was made because these lines fall on a curve shaped much like a normal self-reversal curve, and they were measured at the same time as multiplets having much more self-reversal. It is believed that the present interpretation is the correct one, although the resemblance to self-reversal is striking. The satellites are anomalous in any case, and one strong line is missing.

TABLE 8. *Multiplet 244.*

		b^4D 4	3	2	1	0	Sum
	5	*s* 220 117	x	x	x	x	220 117
	4	*y* 30 26	*t* 150 106	x	x	x	180 132
a^5F	3	2 —	*x* 42 32	*u* 96 96	x	x	140 128
	2	x	4 —	40 0	*v* 56 <57	x	100 <57
	1	x	x	4 —	28 0	*w* 28 17	60 17
Sum		252 143	196 138	140 96	84 57	28 17	

Notes: No pair of normal lines. Line *u* taken as normal. Two strong first order satellites missing.

TABLE 9. *Multiplet 253.*

		a^4G 6	5	4	3	2	Sum
	6	*c* 971 520	*p* 69 0	x	x	x	1040 520
	5	*m* 69 1580	*d* 710 480	*a* 101 100	x	x	880 2160
a^4G'	4	x	*o* 101 2200	*h* 520 315	*f* 99 100	x	720 2615
	3	x	x	*r* 99 1620	*n* 394 340	*j* 67 108	560 2068
	2	x	x	x	*u* 67 900	*q* 333 815	400 1715
Sum		1040 2100	880 2680	720 2035	560 1340	400 923	

Notes: *a* and *f* taken as normal. Multiplet characterized by extreme asymmetry of satellites, one strong line missing.

TABLE 10. *Multiplet 254.*

		a^5H' 7	6	5	4	3	Sum
	6	*k* 1080	*g* 63	*b* 1.3	x	x	1165
		c 2340	735	40			3115
	5	x	*t* 873	1 92	*e* 2.4	x	968
			873	603	43		1519
a^5G'	4	x	x	*v* 699	*p* 92	*i* 2	793
				698	487	30	1215
	3	x	x	x	*w* 554	*s* 62	616
					575	248	823
	2	x	x	x	x	*x* 440	440
						445	445
Sum		1080	936	793	649	504	
		2340	1608	1341	905	723	

Notes: Lines *t*, *v*, *w*, and *x* taken as normal, although they are relatively the four weakest lines. The multiplet is characterized by the extreme strength of the leading line, and of all the satelllites.

TABLE 11. *Multiplet 258.*

		d^4F' 5	4	3	2	1	Sum
	5	*b* 475	*a* 53	x	x	x	528
		202	67				269
	4	*i* 53	*d* 304	75	x	x	432
		57	172	0			229
a^5F	3	x	*k* 75	*f* 189	*c* 72	x	336
			45	176	52		273
	2	x	x	*l* 72	*g* 120	*e* 48	192
				49	120	112	281
	1	x	x	x	*j* 48	*h* 96	144
					38	22	60
Sum		528	432	336	192	144	
		259	284	225	210	134	

Notes: Lines *g*, *i*, and *f* taken as normal. Multiplet is characterized by one strong line missing, and by the asymmetry of some of the satellites, together with the unevenness of the main lines.

TABLE 12. *Multiplet 278.*

		a^5F' 5	4	3	2	1	Sum
	6	*m* 546 558	x	x	x	x	546 558
	5	46 0	*n* 416 1020	x	x	x	462 1020
a^5G'	4	1.8 —	67 0	*o* 309 309	x	x	378 309
	3	x	3.4 —	66 0	125 0	x	295 0
	2	x	x	3 —	45 0	*p* 162 154	210 154
Sum		594 558	486 1020	378 309	270 0	162 154	

Notes: *m*, *a*, and *p* taken as normal. Multiplet characterized by one extra-strong line, and by the fact that one main line and all the satellites are missing.

DISCUSSION OF RESULTS

The following are the chief characteristics of the multiplets in the complex super-multiplet, as made evident in Tables 4–12:

1. None of the multiplets has line intensities even approximately obeying the intensity formulas or the Sum Rule.

2. In no multiplets do more than four lines have normal intensity ratios among themselves; in some cases no two lines have the predicted ratio.

3. Many lines predicted by the formulas to have relatively high intensities are entirely missing.

4. No similarity of abnormality is noted between multiplets of the same type.

5. Even if self-reversal were present, or if excitation corrections were necessary, the abnormalities are not of the type that could be caused by errors due to these.

6. Multiplet 254, $a^5G'-a^5H'$, is characterized by a leading line of abnormally high intensity, and four other main lines of normal intensity relative to one another. The four a^5F-a^5H' lines of Multiplet 241 arise from the same upper states as the four normal lines of 254. This would seem to indicate that the leading line $254-k$ should be taken as normal,

while the four lines $254-t$, v, w, and x are weakened by the abstraction of energy by the ${}^5FH'$ lines, and by the satellites of 254. These are abnormally strong, but when the proper lines of 254 and 241 are added for the common upper states, the Sum Rule appears to hold for the first two or three sums, but the totals fall off in intensity progressively for the remainder. At first it was believed that this might be due to experimental error, the tendency being to over-correct weak lines for background, thus making the weak lines less intense than they should be. The agreement of the values obtained from a number of different plates, and the fact that the actual intensities of a given line were varied ten-fold, lead me to believe that the deviation from the Sum Rule is real, however.

TABLE 13.

Upper state	Term value	$\Delta\sigma$	Intensity sum	Sum / $2J+1$	R_m	R for 2080°	Reduced sum / $2J+1$
a^5H_7'	42205	491	700	46.7	1.01	1.41	65.9
a^5H_6'	42123	409	616	47.5	.99	1.33	63.2
a^5H_5'	42018	304	487	44.3	1.07	1.24	55.0
a^5H_4'	41917	203	379	42.1	1.12	1.15	48.5
a^5H_3'	41823	109	241	34.4	1.37	1.08	37.2
a^5G_6	42019	305	547	42.0	1.12	1.24	52.0
a^5G_5	41903	189	<600	<54.6	—	1.13	<61.8
a^5G_4	41818	104	489	54.2	0.87	1.07	58.0
a^5G_3	41757	43	344	49.2	0.96	1.02	50.2
a^5G_2	41714	0	236	47.2	1.00	1.00	47.2
d^5F_5'	43330	1616	164	14.9	3.16	3.02	45.0
d^5F_4'	43231	1517	182	20.2	2.33	2.82	57.0
d^5F_3'	43148	1434	92	13.1	3.60	2.70	35.4
d^5F_2'	43081	1367	75	15.0	3.14	2.58	38.7
d^5F_1'	43034	1320	49	16.3	2.90	2.50	40.7
b^5D_4	42184	470	297	33.0	1.39	1.40	46.2
b^5D_3	42052	338	316	45.2	1.04	1.27	57.5
b^5D_2	41958	244	<269	<53.8	—	1.19	<64
b^5D_1	41901	187	<137	<45.6	—	1.13	<52
b^5D_0	41871	157	28	28.0	1.68	1.11	31.2
b^5P_3'	42858	1144	152	21.7	2.17	2.22	46.0
b^5P_2'	42724	1010	144	28.8	1.64	2.00	57.5
b^5P_1'	42611	897	95	31.6	1.49	1.86	59.0
Average deviation from mean				33%			17%

It is obvious that we are dealing here with an anomaly at least as great as Degree 3 of the list above, and in order to test the degree further it is necessary to consider the super-multiplet as a whole. The excitation conditions must be considered in this case, however. In Table 13 are given the various upper terms involved, together with the sums of all the intensities arising in the super-multiplet from these upper terms, in Column 4. In Column 5 are given the sums divided by Lande's inner quantum number $2J+1$. If the Sum Rule were fulfilled horizontally for the super-multiplet as a whole, this number should be a constant. Its departure from constancy might be due to the fact that the upper states were not being excited in accordance with their a priori probabilities. In Column 3 are given the wave-number separations $\Delta\sigma$ from the lowest upper state a^5G_2.

In order to apply the proper correction, each I value should be multiplied by a certain ratio R obtained from the Boltzmann formula

$$R = \frac{e^{-E_1/KT}}{e^{-E_2/KT}} = e^{hc/KT\,(\sigma_2-\sigma_1)}$$

where σ = wave-number and the other letters have the usual meaning. Introducing the values of the constants we reduce this to the form $\Delta\sigma = (T/.625)\ \log_{10} R$, where $\Delta\sigma = \sigma_2 - \sigma_1$. If we then plot $\Delta\sigma$ against $\log_{10} R$ as in Fig. 4, we should obtain a straight line. We are here treating the temperature as unknown, to be obtained from the slope of the line, and are calculating directly the R values needed to make $I/2J+1$ constant and equal to 47.2, the value measured for a^5G_2. The values of R needed are given in Column 6 of Table 13. It is evident from an inspection of Fig. 4 that no single straight line can be drawn through all the points, or even through the majority of them. This indicates at once that this super-multiplet can never be made to obey the Sum Rule horizontally by applying an excitation corresponding to a single temperature.

As to the exact value of the excitation which should be applied, the best we can do seems to be to draw the line as in Fig. 4. We recognize that some excitation correction is undoubtedly necessary, and while we have no means of getting the exact one, this will do as a first approximation. The line drawn corresponds to a temperature of 2080°A., which is considerably lower than the temperatures around 7500°A., which have been found in the case of triads originating lower in the atom, as in Paper II.[8] However, the pressures used in the present

[8] G. R. Harrison and H. Engwicht, this journal, *18*, p. 287; 1929.

case were much higher than those used in that work, and the resulting lower mean free path of the electrons would doubtless cut down their equivalent temperature. 2080°A will serve as one extreme value; the assumption that the temperature was infinite, with no excitation correction necessary, gives the other extreme. We then find that the super-multiplet is anomalous in any case, the Sum Rule not being obeyed horizontally when the proper values of R of column 7 are taken from the 2080° line, giving the horizontal sums shown in Column 8.

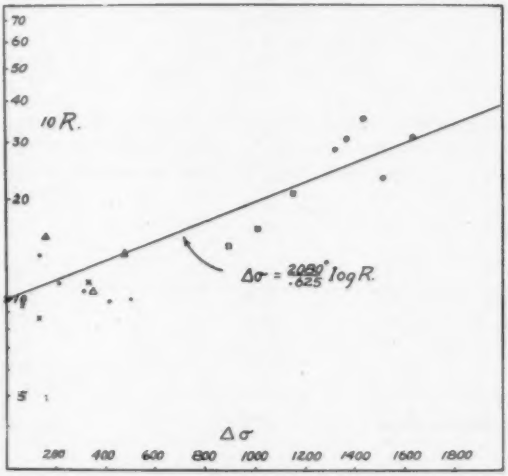

FIG. 4. *Plot of wave-number separation Δσ of the various upper states from the lowest upper state, against the logarithm of the ratio of the sum of the intensities of lines arising from a common upper state divided by 2J+1, to this sum for the lowest upper state divided by 2J+1. The line as drawn represents a temperature of 2080°; the deviation of the points shows that the line sums are extremely anomalous.*

The vertical sums for the super-multiplet are given in Table 14, both with and without excitation corrections. It is obvious that the Sum Rule does not hold in this direction either. We thus see that the anomaly is at least of Degree 6 of the table given above.

It is of interest to compare the total intensity of each multiplet with the predicted values given by Kronig's formulas. This is done in Fig. 5, the excitation correction having been applied as of 2080°A. The effect of this correction on the individual multiplets is shown in Fig. 6, where the points, if the multiplets were normal, should all lie

on the 45° line. The crosses represent the values without excitation correction, while the circles show the corrected values. It is evident that no excitation correction for any single temperature could make the intensities fit exactly.

TABLE 14.

Lower state	Sum without correction divided by $2J+1$	Sum with excitation correction for 2080°, divided by $2J+1$
a^5G_6'	78.3	110.0
a^5G_5'	70.0	89.5
a^5G_4'	64.0	76.0
a^5G_3'	73.5	80.0
a^5G_2'	72.3	76.4
a^5F_5	53.4	80.0
a^5F_4	56.6	75.4
a^5F_3	60.5	81.2
a^5F_2	52.5	83.0
a^5F_1	48.3	57.4
a^5D_4'	47.5	95.0
a^5D_3'	56.8	104.0
a^5D_2'	50.8	78.0
a^5D_1'	53.0	75.2
a^5D_0'	70.0	101.0
Average deviation from mean	15%	12%

In Fig. 5, the first figures represent the computed intensities, while those following represent the deviation of measured values from computed values. These have been calculated on such a basis that the greatest number of sums would come out approximately normal; even so, it is obvious that a large degree of anomaly exists.

We thus conclude that in order to fulfill the Sum Rule with these lines it is necessary to treat at least an enlarged super-multiplet, consisting of this super-multiplet, the corresponding one in the triplet system, and all their inter-system combination lines. We find, however, that of the triplet upper states, only e^3F' and c^3G have been found, the proper $^3P'$, D, and H' terms not being given by Russell. Certain intercombination lines of type $a^5D'-e^3F'$ (Multiplet 212) and a^5F-e^3F' (Multiplet 240) are given, however, and the intensities of these have been measured and are given in Table 2. Their total intensities do very little to improve the vertical sums, however.

	a^5G'	a^5F	a^5D'	Σ
a^5H'	264·18	0 ·33	×	264·15
a^5G	81 ·19	135 ·31	×	216·12
d^5F	15 ·2	105 ·36	48 ·5	168·29
b^5D	×	40 ·2	80 ·3	120·1
b^5P'	×	×	72 ·0	72·0
Σ	360·3	280·36	200·8	

FIG. 5. *Intensities of multiplets in the complex super-multiplet, after a temperature correction for 2080° has been applied. The first numbers in each square represent the intensities calculated from Kronig's formulas; the numbers added or subtracted represent the deviation of measured values from computed.*

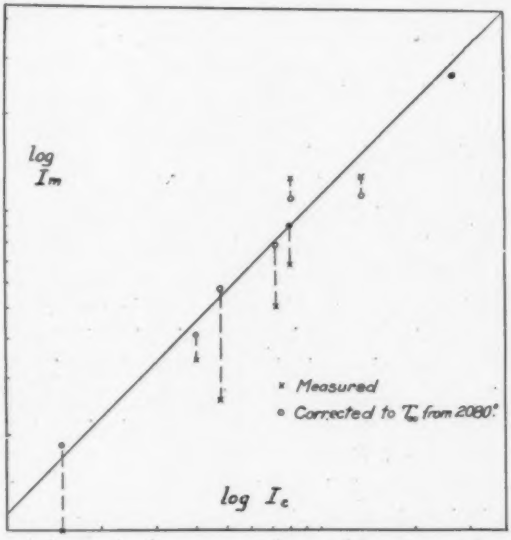

FIG. 6. *Plot showing the effect of the 2080° excitation correction on the relative intensities of the multiplets in the complex super-multiplet. Crosses represent uncorrected, circles corrected values. No temperature correction would make the points lie on the 45° line, indicating that the intensities are truly anomalous.*

We conclude, and indeed the presence of the $^5FH'$ lines in the super-multiplet would lead us to suspect this in any case, that in order to fulfill the Sum Rule here, at least all of the lines originating from the parent term a^4F' by the addition of an electron undergoing the transition $4d-4p$ must be included. It may well be that even this will not be enough, for the configuration change $(3d)^34s4d-(3d)^34s4p$ involves many lines in addition to those arising from the parent terms a^4F'. There seems to be nothing fundamentally abnormal about these parent terms, since multiplets having them as final states have been found normal in Ti II (see Paper I)[9], and its intervals obey Lande's rule fairly well.

In the complex super-multiplet considered, however, numerous other features besides the intensities are anomalous. The intervals are in some cases anomalous and in some normal; the intermingling of the various levels of the upper states with one another reminds one forcibly of the similar characteristic in the singlet-triplet case found theoretically by Houston[4] to be connected with anomalous intensities.

The fact that the lines are nebulous in the furnace and in the arc at atmospheric pressure, while they are sharp in the vacuum arc, indicates, as Dr. Russell has pointed out to the writer, that they are abnormally sensitive to external conditions. That these do not greatly affect the relative intensities, however (except possibly in one or two striking cases which are to be investigated in this regard) is indicated by the parallelism obtained in most cases between King's intensity estimates and the quantitative determinations of the present paper.

The writer has been informed by Professor Ornstein that a number of multiplets of nickel and cobalt have been measured at Utrecht, the results not yet having been published, and that no multiplets were found to obey the formulas. The sums were in general as anomalous as those given above. Strong inter-combination lines and other lines forbidden by the selection principles are also found in these spectra; such anomalies are generally found to increase from element to element as we proceed from left to right across the Periodic Table. Titanium is one of the left-hand elements, and the measurements made to date have shown the majority of its lines to be normal in intensity; the presence in its spectrum of such an anomalous group of lines as those discussed here should be of importance in determining the factors causing the change from the simple intensity relations given by the early formulas to those complex ones not yet obtained theoretically.

[9] G. R. Harrison, this journal, *17*, p. 389; 1928.

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DEPARTMENT OF PHYSICS,
STANFORD UNIVERSITY
PALO ALTO, CALIFORNIA.
JUNE 29, 1929.

Willmer Ophthalmological Institute. Exercises for the dedication of the Wilmer Ophthalmological Institute will be held October 15, and 16, 1929, under the auspices of the Johns Hopkins University, the Johns Hopkins Hospital and the William Holland Wilmer Foundation. An appropriate program has been arranged including the following addresses: "The Development of Ophthalmology in Europe," by Hofrath Ernst Fuchs, of the University of Vienna; "Some Contributions and Phases of American Ophthalmology," by Dr. George E. de Schweinitz, of the University of Pennsylvania; and "Color Vision and its Anomalies," by Sir John Herbert Parsons, of the University of London.

OPTICAL SOCIETY OF AMERICA

NOTICE OF CHANGE OF SECRETARY

Professor C. C. Bidwell's resignation as secretary has been accepted to take effect July 1, 1929.

Dr. L. B. Tuckerman has been appointed to serve the unexpired term of secretary, July 1, 1929, to December 31, 1930.

Communications to the secretary should be addressed:

Dr. L. B. Tuckerman, Secretary,
Optical Society of America,
Bureau of Standards,
Washington, D. C.

The following resolution relative to change in the office of secretary has been duly adopted by the executive council.

Whereas Prof. C. C. Bidwell has tendered his resignation as secretary of the Optical Society of America to take effect at a date to be set by the council, and

Whereas the president has nominated Dr. L. B. Tuckerman to serve the unexpired term of Professor Bidwell,

Be It Resolved:

(1) That the council tenders its thanks to Professor Bidwell for the services he has rendered the society during his term of office, and regrets that the pressure of other duties makes it impossible for him to continue to discharge the duties of that office;

(2) That Professor Bidwell's resignation be accepted to take effect July 1, 1929;

(3) That the appointment of Dr. L. B. Tuckerman to serve the unexpired term of secretary from July 1, 1929, to December 31, 1930, is hereby approved.

IRWIN G. PRIEST, *President*

WASHINGTON, D. C.,
JUNE 26, 1929.

INSTRUMENT SECTION

SOME CHARACTERISTICS OF PHOTOELECTRIC TUBES

By Lewis R. Koller

When Hertz made his first observations on the photoelectric effect, he wrote to a friend that he had observed a new phenomenon. At that time it was not only new but also totally unrelated to any other physical phenomena. Since 1887 many others have followed Hertz in this field and the photoelectric effect has been found to be closely related to many other physical facts. It is the purpose of this article to discuss some of its more outstanding features, particularly those in which recent progress has been made.

Hertz observed that a spark passed more readily across a spark gap when it was illuminated by the light of another spark. Hallwachs investigated the phenomenon further and found that light, particularly light of short wavelength, caused a negatively charged metal plate to lose its charge.[1] It has since been found that some insulators also show the same effect. They have not however been as thoroughly investigated as the metals.

It remained for J. J. Thomson to show that this loss took place through the agency of the then newly discovered electron.[2] Dember[3] demonstrated that this emission took place even in the best attainable vacuum, a fact which is taken for granted now, although this was not the case in the early days of high vacuum experimentation.

It soon became apparent that the photo current was a function of the light intensity or the total flux reaching the cell. This was first investigated by Elster and Geitel[4] and later by Lenard and by Richtmyer who found that the photo current was directly proportional to the amount of light entering the cell. Ives, Dushman and Karrer and Kunz have found deviations from this law of direct proportionality, but there is evidence to indicate that they may be due to disturbing factors such as charging up of the bulb wall or to space charge.

Fig. 1 shows the relation between photo current and illumination for a certain type of gas filled photo cell. The deviation from a straight line is most marked at high voltages and high intensities.

[1] Ann. d. Physik, *33*. p. 301: 1888.
[2] Phil. Mag., *48*, p. 547; 1899.
[3] Ann d. Phys., *30*. p. 152; 1909.
[4] Ann d. Physik, *48*, p. 625; 1893.

Vacuum cells give a more nearly linear response to light intensity but also show deviation in the same direction as the gas filled cells. These facts have not yet been satisfactorily explained. The characteristic can usually be improved by a proper selection of anode voltage.

In the case of gas filled cells, the photo electrons liberated from the cathode by the action of light produce ionization by collision with gas molecules in the space between the electrodes. This fact is made use of in order to produce a true multiplication of the photo current. By this means the original current due to electrons liberated at the cathode may be safely multiplied by a factor of 10.

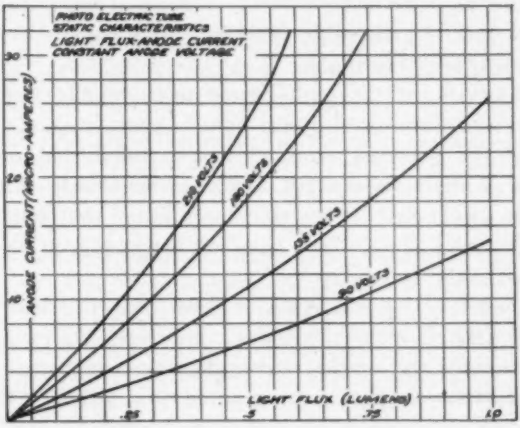


FIG. 1.

The gas used in a photoelectric cell must have two important properties. It must not react chemically with the photo sensitive surface and it must not "clean up." The phenomenon of "clean up" is a common one in any type of tube where gas is ionized. Positive ions under the influence of the electric field are driven into the walls or other parts of the container and thus the gas pressure is permanently lowered. On account of clean-up, nitrogen and hydrogen cannot be satisfactorily used in tubes although hydrogen has been used (N. R. Campbell: Phil. Mag., *37*, p. 633; 1928) in a tube with a palladium tube for replenishing the supply. The only gases which satisfy all of the requirements are the rare gases of the atmosphere. Argon is most satisfactory, due to its low ionizing potential but neon and helium are also used.

Where the photo sensitive surface is apt to be injured by positive ion bombardment, helium might be used instead of argon as helium causes less sputtering than argon Langmuir-Kingdon. (Phys. Rev., *22*, 1923). Helium however is not very effective in amplifying the photo current.

The higher the potential difference between electrodes, the more effective are positive ions in sputtering caesium atoms from the cathode surface. Fig. 2 shows the effect of various voltages upon a certain type caesium cell. At 120 volts the emission falls off rapidly with time, whereas at 60 volts it remains constant. Life tests on this particular type have run for thousands of hours (at voltages below 100) without the slightest indication of deterioration, while at 120 volts the emission falls off rapidly within a few hundred hours.

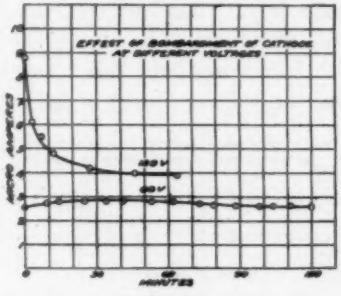


FIG. 2.

As the anode voltage is increased, the current rises more and more rapidly until a critical voltage is reached and the tube breaks into a blue glow. In this condition, the discharge is self sustained and the current is entirely independent of illumination and will continue if the exciting source of light is removed. This subject has been very thoroughly discussed by N. R. Campbell in two articles in the Phil. Mag.[6] He distinguishes between two types of glow discharge. The one type takes place at low light intensities and there is a sudden abrupt rise in current at the glow point. The other, at higher light intensities, takes place gradually with no break in the volt ampere curve. The only indication that the cell is glowing is the fact that the current persists when the light source is removed. Between these two types there is a transition region. The form of the curve, is, of course, a function of the cell construction.

[6] N. R. Campbell Phil. Mag., *3*, p. 945; 1927. Phil. Mag., *3*, p. 1041; 1927.

The nature of the emitting surface, however, is also a factor in determining the glow point. Table 1 gives the glow voltages for two cells of the same construction and very nearly the same sensitivity under the same conditions of illumination and at the same pressure of

TABLE 1.

Illumination intensity 100 watt lamp at	Glow voltage	
	K	Cs
1 ft.	170	150
2 ft.	190	150
3 ft.	220	160

argon. The first column gives the illumination intensity, the second gives the glow voltage for a potassium cell, the third for a caesium cell of the monatomic film type. The former shows a glow potential which decreases with increasing light flux. In the second case, the glow potential is practically independent of light flux.

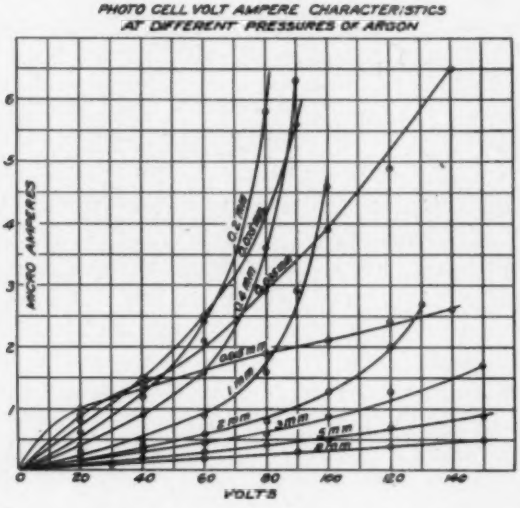


FIG. 3.

As the gas pressure is increased, the probability of collision increases, and accordingly the current at a given voltage will increase. The limit is reached when the mean free path of the electrons in the gas

becomes small compared with the distance an electron must travel to acquire sufficient energy to ionize.

The curves of Fig. 3 show the effect on the volt-ampere characteristic of various pressures of gas in the same cell. As the pressure is increased, the volt-ampere curve is raised and becomes steeper. A limiting value of pressure, however, is reached where the curves fall and become less steep. Fig. 4 shows the sensitivity at a given voltage as a function of pressure. The maximum sensitivity occurs at a pressure of 0.2 mm. Cells are usually filled at somewhat lower pressures than this, however, in order to obtain greater stability. While the sensitivity

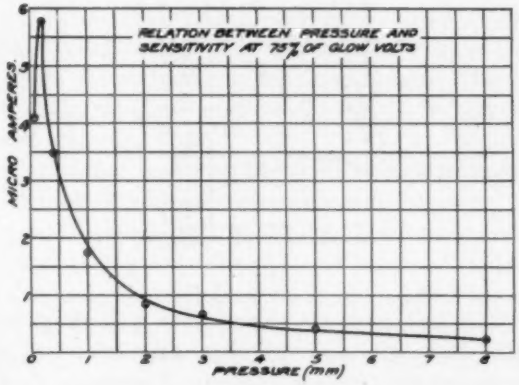


FIG. 4.

is passing through a maximum, the glow voltage is passing through a minimum.

The spacing between the electrodes is not of great importance in so far as it affects the total current. Fig. 5 shows how increasing the distance between parallel plane electrodes, while the voltage was kept constant, affected the sensitivity. This experiment was performed in a tube with a cathode, consisting of a flat disc, which could be moved by means of a magnet. The anode was in the form of a grid parallel to the cathode. The sensitivity passes through a maximum, but it is so flat that wide latitude may be allowed in design.

Naturally the early investigations of this subject turned toward a comparison of the photoelectric activity of different materials. The alkali metals were found to be particularly active, but comparisons of this kind must be qualified because each element shows a character-

istic response to light of different wave length, and while two elements may appear in a certain order as regards photoelectric activity at one wave length the order may be entirely reversed at a different

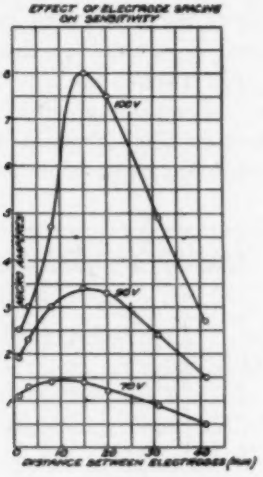


FIG. 5.

frequency. This feature of the phenomenon was recognized early by Herz and Hallwachs who observed that ultraviolet was particularly effective in causing the emission of photo electrons.

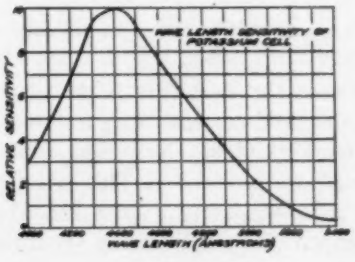


FIG. 6.

The group which has been studied most thoroughly is that of the alkali metals. These are all sensitive to some extent to visible light. In Fig. 6[6] is shown the wave-length sensitivity curve for potas-

[6] Data taken from E. F. Seiler, Astrophys. Jour., *52*, p. 129; 1920.

sium. It represents the relative photo currents for equal amounts of energy throughout the spectrum. This curve is typical of the whole group, showing a sharp maximum at the edge of the ultraviolet and then a gradual drop to a limiting wave length in the yellow red known as the long wave limit. Light of longer wave length will not liberate any electrons. As we proceed through the alkali metal series, we find that the position of the maximum as well as the long wave limit is shifted towards the red, so that lithium, while highly sensitive to ultraviolet, is nearly insensitive to visible light, while the curve for caesium extends further into the visible than that for any of the other elements of this group. The latter is the most red sensitive substance known at present. (Selenium, thallium oxy-sulphide, copper oxide, molybdenite and some other natural minerals show very large changes in conductivity under the influence of red or infrared.) The formation of hydrides of these metals in each case displaces the curve slightly towards the red.

Magnesium, cadmium, and zinc are sensitive to ultraviolet. Satisfactory data are available only for a very few substances.

The shape of this wave-length sensitivity curve, however, depends upon other factors than merely the chemical nature of the element in question. It is to some extent influenced by the polarization and angle of incidence of the light and very greatly by the nature of the photo sensitive surface. Ives[7] has shown that very thin films of the alkali metals have long wave limits further in the red than thick films and this red sensitiveness passes through a maximum for a definite thickness. At the same time the total sensitivity to any wave length increases as well. The writer has shown in the case of potassium that the maximum sensitivity is obtained for a layer of potassium one atom deep.

In the case of caesium it has been possible[8] to obtain a wide variety of sensitivities depending upon the nature of the surface. Miss Seiler[9] and others who have studied caesium in bulk have obtained a curve with a maximum in the visible spectrum at about $\lambda = 5400$ which corresponds very closely to the maximum wave length of the human visibility curve. Zworkin[10] found the maximum to be at about $\lambda = 4850$ for a monatomic film of caesium on magnesium. If a monatomic film of caesium is deposited on a layer of oxygen on a silver back ground,

[7] Astrophysical Jour., *60*, p. 209; 1924.
[8] Charlton and Bainbridge, Science, 1929.
[9] V. Zwarykin and E. D. Wilson, Phys Rev., *33*, p. 633; 1929.
[10] N. R. Campbell, Phil. Mag., *6*, p. 633; 1928.

the maximum is shifted towards the ultraviolet and the long wave limit towards the red. If instead of a monatomic layer of Cs on O_2 on Ag a layer of caesium on caesium oxide is formed no change takes place in the short wave maximum but a remarkable hump appears in the red and the long wave limit moves out towards the infrared. This increased red sensitivity is characteristic of compound formation although it has never before been observed to such a marked degree. A similar but smaller effect has been reported by N. R. Campbell[11] in the case of potassium on oxygen on copper. In both of these cases,

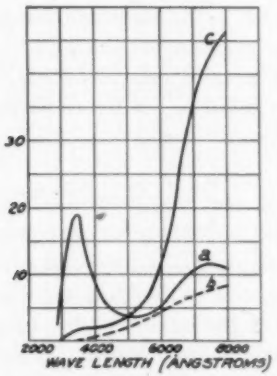


FIG. 7a. *(a) Relative sensitivity to equal energy spectrum. (b) Energy distribution of black body at 2800° K. (c) Relative sensitivity to black body at 2800° K.*

the procedure is to distill the metal onto the oxidized surface and then by heating to reduce some of the oxide and drive out the excess metal. This leaves a spongy deposit of the oxide of alkali metal with an adsorbed film of the metal. Any free metal tends to lower the sensitivity.

The color sensitivity of cells is of considerable practical importance. In some cases their selectivity is a great disadvantage, in others a great help. Wherever the cell is used with any incandescent source of light and it is desired to obtain the maximum possible output, red sensitivity is a great advantage. Fig. 7A shows the wave-length sensitivity curve for a Cs-CsO-Ag tpye of cell together with the energy distribution of a black body at 2800° K. Multiplying the ordinates gives the total sensitivity of the cell to this source. Fig. 7B shows similar data for a monatomic film type of cell. Thus although the areas under the two sen-

[11] Loc. cit.

sitivity curves are only in the ratio of 2 to 1 the sensitivities of the two cells for this type of source are in the ratio of 6 to 1.

The knowledge of the behavior of thin films has led to changes in photo cell construction. The earlier types had cathodes consisting of a heavy deposit of the photo sensitive elements. In the more recent types where the sensitive surface is extremely thin, it is deposited upon a conducting metal background. This either takes the form of a plate or of a deposit on the bulb wall formed either by chemical deposition from a solution or evaporation as in the case of Ag, Cu, Au, Mg.

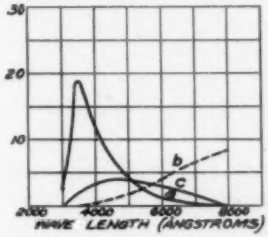


FIG. 7b. *(a) Relative sensitivity to equal energy spectrum. (b) energy distribution of black body at at 2800°K. (c) Relative sensitivity to black body at 2800°K.*

The alkali metal may be distilled in directly from a piece of the metal placed in a side tube, or it may be formed in the tube by a reaction of the type

$$2\,Cs\,Cl = Ca \rightarrow CaCl_2 + 2\,Cs$$

or by the breaking down of a compound such as

$$Ba\,N_6 \rightarrow 3N_2 + Ba$$

or by simple evaporation of the metal within the tube as in the case of Zn, Mg, or Cd.

Most photoelectric cells are not sensitive to small changes in temperature. Potassium hydride cells, when heated to temperatures in excess of 60° C, show a marked drop in sensitivity which is not regained again on cooling. This is due to dissociation of the hydride. This phenomenon, of course, is distinct from any true temperature coefficient of photoelectricity.[12] The monatomic film type of cell is stable up to at least 100 C. and shows no change when operated for several hours at this temperature.

[12] H. Elves and A. L. Johnsrud, J. O. S. A. & R. S. I., *11*, p. 565; 1925.

The number of applications of the photoelectric cell is limited chiefly by the imagination of the user. Perhaps the earliest application was to the photometry of lamps. A number of photoelectric cell photometers are at present in actual operation.[13] With slight modifications, the cell takes the place of the eye at the photometer head and so eliminates the human equation. One of the difficulties encountered is the fact that the color sensitivity of the cell differs from that of the human eye so that the cell does not evaluate correctly when lights of different colors are to be compared. This can be compensated for by suitable color filters adjusted to the cell.

The photo cell is also used in studying and making continuous records of variations in light intensity, daylight ar artificial. Quartz cells with cathodes which are not sensitive to visible light are used for measurements of the ultraviolet in the solar spectrum and for studying other sources of ultraviolet. Such a cell is a valuable aid in determining quantitatively the amount of ultraviolet obtained from the various sources used for therapeutic work and in measuring the deterioration of such sources.

Photo cells have also been used in a device by means of which a complete quantitative spectrophotometric analysis is made of any reflecting surface.[14]

They are also a convenient tool for making measurements of the transmission or absorption of liquids, solids or gases and will respond to differences which cannot be detected by the eye.

The two best known applications are television and the talking moving pictures which have been fully discussed elsewhere. A partial list of industrial applications includes cigar sorting; airport lighting; traffic control; railway signal control; elevator control; testing of dyes, quality of paper, oils, etc. In general, photoelectric cell application may be divided into two groups, control devices and quantitative measuring devices. In the first type of application they must respond to a change in light intensity, which may be quite large, and operate a relay or some substitute for a relay such as a thyratron tube by means of which other apparatus is controlled. In the other type of application they may be used to perform a chemical analysis, as, for example, by measuring the absorption or reflection of light by a sample of material,

[13] W. F. Little and C. E. Horn, Trans. Ill. Eng. Soc. 1927.
C. H. Sharp and H. A. Smith, Trans. Ill. Eng. Soc. 1927.
C. Deschler and H. Shroeder, Trans. Ill. Eng. Soc. 1927.
[14] Hardy, J.O.S.A. & R. S.I., *18*, p. 165; 1929.

to make spectrophotometric measurements or to photometer lamps.

In most cases, a system of resistance coupled amplification is used, the drop across a high resistance in series with the cell being applied between grid and filament of three electrode tube. If this is not sufficiently sensitive, a bridge method such as the one shown in Fig. 8 is used. This type of circuit is discussed by J. M. Eglin in the May 1929 Journal of the Optical Society.

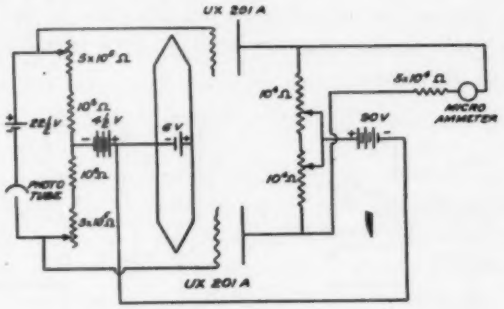


FIG. 8.

If the currents are extremely small and comparable with leakage currents, then dc. amplification is no longer possible and ac. amplification must be resorted to. The ac. input is obtained by interrupting the light beam by means of a sector disc or a toothed wheel which may have its teeth so cut as to give any desired wave form. The result is an ac. output of amplitude varying with the intensity of the light source.

Research Laboratory,
General Electric Company,
Schenectady, New York.
MAY 16, 1929.

A VACUUM ARC

By Vernon M. Albers

In spectroscopic work, it is sometimes desirable to operate an arc in air at reduced pressures, or in an atmosphere of some gas other than air. When this is done it is necessary to operate the arc in a closed chamber and some device must be used to strike the arc from the outside. The arc described below was designed by the author and was used in studying the spectrum emitted by a beryllium arc in an atmosphere of hydrogen.

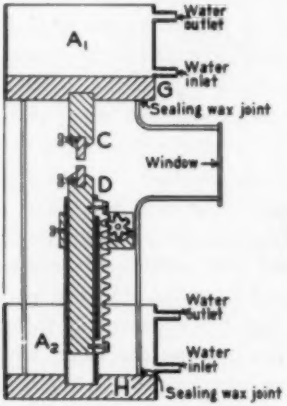


Fig. 1.

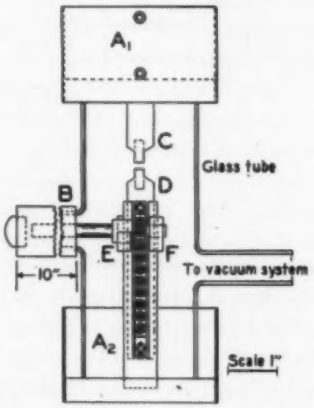


Fig. 2.

The electrodes, C and D, (Figs. 1 and 2) are ½ inch iron rods each of which has a hole 1/8 inch in diameter drilled in the end, with a set screw for securing a small rod of the material to be used in the arc. The electrode, C, is soldered to the center of a brass disc, G, ½ inch thick and 3 inches in diameter which is supplied with a water cooling jacket A_1. The electrode, D, is mounted in a brass tube with ½ inch inside diameter and this brass tube is soldered to the brass disc, H, which is similar to the disc, G, and is supplied with the water cooling jacket, A_2. In order to strike the arc the electrode, D, may be raised by means of a rack and pinion until it touches C and then lowered to the position shown in the figure. The rack is fastened to the movable electrode and may be moved up and down in a slot cut

in the brass tube. The pinion is mounted on a shaft 11 inches long, which projects through a side tube sealed on the side of the glass chamber containing the arc. A piece of soft rubber pressure tubing, with one end stopped by means of a glass rod, is slipped over the shaft and over the end of the side tube through which the shaft projects. By pinching the pressure tubing and twisting it the pinion may be rotated without danger of starting a leak in the vacuum system. The bearings, E and F, (Fig. 2) support the pinion. The bearing at F is $\frac{1}{4}$ inch in diameter and the one at E is $\frac{1}{2}$ inch in diameter, or the same diameter as the pinion. This arrangement of bearings makes it possible to slide the shaft carrying the pinion into place through the side tube, B, (Fig. 2) making it possible to assemble the arc inside the chamber.

The chamber was made from a piece of 60-mm, heavy, pyrex tubing which was cut off and the ends ground so that they were perpendicular to the axis of the tube. The tube is waxed to the discs supporting the electrodes with sealing wax and the discs are maintained at a low enough temperature, by means of the water jackets, so that the wax does not soften. A 30-mm side tube is sealed to the chamber opposite the arc and the end of this tube is closed with a quartz plate held in place with sealing wax. This side tube is about 10 cm long so that the window is not easily fogged by vapors from the arc.

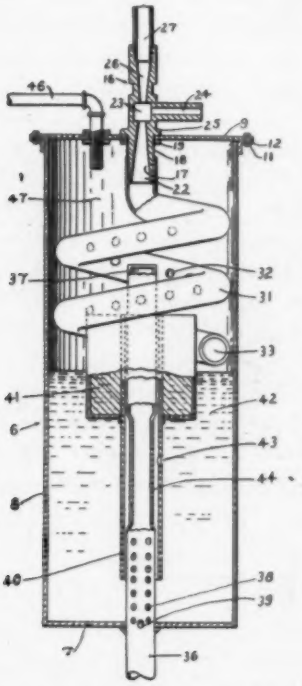
By means of this apparatus it is possible to maintain an arc in any desired atmosphere at any pressure and it is almost as easy to strike the arc inside the chamber as it would be to strike one out in the open.

DEPARTMENT OF PHYSICS,
EASTERN KY. STATE TEACHERS COLLEGE
RICHMOND, KY.

AIR COMPRESSOR FOR SMALL LABORATORIES

By Harry Gilbert and Walter Gilbert

Laboratory workers frequently have use for small quantities of compressed air at comparatively low pressure. The expense involved in the installation of motor driven blower makes such a device unavailable to the small laboratory. The device hereinafter described was designed to supply compressed air to operate a blast lamp. The essential features of the device are:



1. A filter pump of the usual sort (*16* in the diagram)

2. A helical coil *31* of copper tubing which is fastened to the outlet end of the filter pump. Holes are drilled through the tube in the inner surface of this helix as shown in *32* in the diagram.

3. The filter pump with the attached helix is fastened in a container as shown in the diagram.

4. A tube (*36*) closed at the upper end extends vertically upward from the lower end of the container. This tube is perforated near the

lower end as shown in diagram. Perforation *39* serves as a drain when the device is not in use. *44* is a constriction in this tube which allows water to flow freely through opening *43* thus forming a water seal between the slide valve *40* and the tube.

5. The slide valve *40* is operated by float *41*. This float is of such dimension as to slide freely inside the helix. Opening *43* in this valve allows the water to enter between the tube and the slide valve thus preventing a leakage of air from above.

6. *46* serves as the outlet for the compressed air.

The device operates as follows: Water entering through opening *27* rushes past inlet *24* creating a partial vacuum in inlet *24*. The resulting mixture of water and air enter the helix. The separation of the air from the water is greatly enhanced by the centrifugal motion of the mixture passing through this helix. Experiment shows that even when the velocity of the water is high practically all of the air has escaped from the mixture by the time the water emerges at opening *33*. The use of the filter pump without the helix causes so much disturbance as to make the operation of the float impossible unless the whole device is greatly enlarged. The use of the helix here described makes the construction of a very compact device possible.

As the water level rises the float is lifted allowing water to flow through the holes in tube *36*. The amount of this flow is regulated by the height of the water level. If outlet *46* is completely closed the accumulated air and water both flow out through the valve. If outlet *46* is completely opened the rising water opens the valve to such an extent that outflow of the water equals the inflow through the filter pump.

The novel features of this device are:

1. The use of a perforated helix to separate the air from water.
2. The use of a float-controlled sleeve valve to regulate the water level.

The cost of construction of this device is low. The motive power, water, is available in every laboratory. The only moving part is well lubricated by water. The amount of air pressure available with this device will vary somewhat with the strength of construction. We have found that using a home-made apparatus constructed of a tin can, a filter pump, copper tubing, and cork float, we are able to produce sufficient air pressure to blow out the flame of the blast lamp of usual laboratory type.

FRANKLIN HIGH SCHOOL,
LOS ANGELES, CALIFORNIA.

AN AUTOMATIC COOLING SYSTEM FOR THE HADDING-SIEGBAHN X-RAY TUBE

By Gilbert Greenwood

In many x-ray installations it is often found necessary that both the cathode and the anti-cathode should be cooled. In such cases, even when it is possible to ground one side of the tube, one is left with the problem of providing an insulated cooling system. Various methods have been used to do this.* In one arrangement cold water, which is stored in an insulated tank at a higher level than the apparatus to be cooled, is allowed to flow through the system, and is caught in a second insulated tank. Whilst such an arrangement is fairly satisfactory it requires attention every few hours in order to empty the lower tank and to refill the upper one. To avoid this, automatic circulating systems have been devised. In one such system oil is used as the cooling medium. The oil is forced through the system by means of a pump, which must itself be insulated. The oil is then cooled by sending it through the inner tube of a Liebig condenser through the outer jacket of which cold water is flowing. Cooling by such means requires somewhat elaborate apparatus.

It lately became essential to set up some simple cooling system for the cathode of a Hadding-Siegbahn x-ray tube. In this type of tube, the outer metal walls, together with the anti-cathode are grounded, whilst the cathode is maintained at a potential of about 40,000 volts. In the first system to be used, an attempt was made to get circulation set up by convection currents which might be produced by local heating at the cathode. Not much success was obtained in this direction. Finally an automatic circulating system based on the principle of the continuous-acting Sprengel pump was devised. This system has been in use in the laboratory during the past eight months and has proved most satisfactory. It has sometimes been run continuously for as long 30 hours without requiring any attention.

It is shown diagramatically in the attached figure. A supply of cold water—about six liters—is contained in the reservoir *A*. This reservoir is a glass bottle having two openings *B* and *C*. It is mounted on insulating blocks of wax on a shelf high up on a convenient wall. A glass tube leads from the stopper *B* to a water aspirator pump, and by this means a reduction in pressure can be created in the vessel *A* above the

* H. Mark. Die Verwendung der Röntgenstrahlen in Chemie und Technik (Barth), 1926. p. 84.

surface of the water. From the lower opening C of the bottle a tube leads to the inner cooling pipe D of the cathode of the x-ray tube. This cathode is shown in the diagram mounted with its porcelain insulator; the metal part of the tube and the anti-cathode is not shown. Water must flow down this inner tube to the curved end of the cathode where the heat is generated and then return through the outer surrounding tube to the outlet E and finally again to A. This return flow was caused by putting into the return tube, a T-piece just after the out-

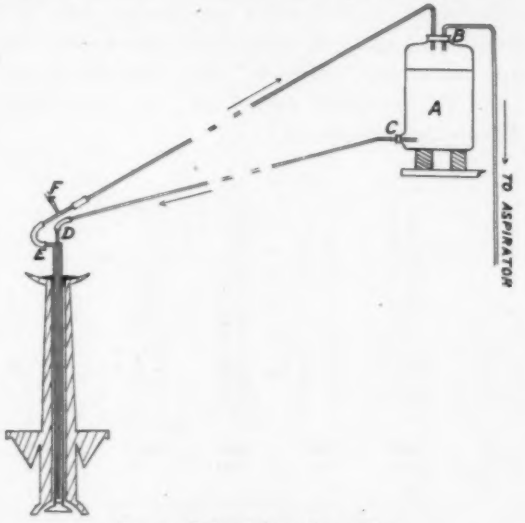


FIG. 1. *X-Ray tube cooling system.*

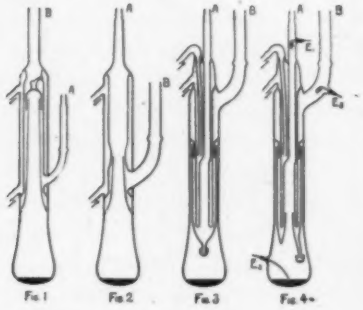
let E. The other limb of the T-piece was closed by a piece of rubber tube and a screw clip F. This screw clip could be opened slightly so that a small quantity of air could be sucked into the system owing to the reduced pressure in A. In this way a broken column of air and water was obtained in the return tube. The effective density of this column is less than that of the water in the upper tube, and thus a stream of water flows down the supply tube, through the cathode, and back to the reservoir A. The air entering the system at F is removed by the action of the pump which maintains the reduction of pressure in A. The air cooling of the water as it flows through the tubes and the reservoir was found to be quite sufficient.

THE PHYSICAL LABORATORIES,
THE UNIVERSITY OF ROCHESTER,
ROCHESTER, NEW YORK.

HIGH VACUUM TECHNIQUE,—EXPERIMENTAL STUDY OF EFFECT OF IONIZATION ON PUMP SPEEDS

By Chas. T. Knipp and P. C. Ludolph

The ever increasing use of high vacua in research and in the industries has given an added impetus to pump design. Our own efforts[1,2] along this line began in 1917 when two designs were drawn up and their construction of common soda glass undertaken (Figs. 1 and 2). These pumps are of the "umbrella" and "vertical nozzle" types respectively, and are externally cooled, i.e., the water jacket is placed outside of the nozzle in each case.



Showing a development in pump design.

Two other interesting and newly designed forms of pumps are being constructed in this laboratory (Figs. 3 and 4). These have *internal* water cooling. Fig. 3 is a single stage, while Fig. 4 is a two-stage pump.

In the single stage pump (Fig. 3) the mercury vapor passes up along the main tube next to the outside wall and is turned down (i.e., deflected back) by the collar which forms the annular nozzle. This construction is similar, in its action, to the umbrella type just referred to. The air is drawn in through *B*. The hot mercury-vapor encounters the water-cooled annular tube within, is condensed, and

[1] Phys. Rev., *9* Series *II*, p. 311; 1917.
[2] Science, N.S., *55*, p. 183; 1922.

trickles back to the boiler through the suspended cup-valve shown. The accumulated air is drawn out through A by the supporting pump.

In the two-stage pump (Fig. 4) the stage having the large annular nozzle is the same as in the single stage of Fig. 3. The other is formed

TABLE 1. *Two-Stage—Internal water cooled (Fig. 4)*

Backing pump, Cenco-Hyvac. Heating energy, 500 watts.
Minimum pressure = 0.1 mm of Hg. Atm. pressure = 740 mm of Hg.

Pressure in system in mm of Hg	Vol. of gas admitted at atm. pressure	Time	Speed of pump in cc/sec.	Probable error in %
.0022	2.51 cc	15 min	940	2
.012	"	2.5 "	1030	2
.02	"	85 sec.	1150	2
.0233	"	70 "	1140	2
.035	"	45 "	1240	3
.054	"	30 "	1150	3
.0742	"	20 "	1240	4
.098	"	15 "	1330	4
.186	"	8 "	1320	5
No ionization. See Curve a, Fig. 9				
.0009	2.51 cc	38 min.	905	2
.0024	"	13.5 "	960	2
.0322	"	60 sec.	960	3
.056	"	30 "	1110	3
.092	"	20 "	1010	4
.20	"	10 "	930	5
Ionization. Flow of air from (+ to −). Curve b, Fig. 9.				
.0017	2.51 cc	21 min.	855	2
.0057	"	6 "	905	2
.0336	"	45 sec.	1230	3
.056	"	24 "	1380	3
.070	"	18 "	1470	4
.1001	"	13 "	1430	4
.170	"	8 "	1360	5
Ionization. Flow of air from − to +. Curve c, Fig. 9.				

by an upward vertical nozzle placed at the lower end and projects up into the inner water-cooled system. Thus the step in going from the single stage to the two-stage is exceedingly simple. The pump shown in Fig. 4 is also supplied with electrodes E_1, E_2, and E_3 for purposes of ionizing the air being pumped through the system.

Defining pump speed[3] as the volume-rate at which a gas must be admitted into a vessel in order to maintain a constant pressure in the vessel under the action of the pump, we have for the speed

$$s = p_a v_a / pt$$

where p is the pressure in the system, p_a is the atmospheric pressure, v_a the volume of air admitted under atmospheric pressure during the interval of time t.

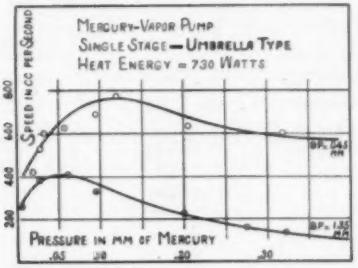


FIG. 5.

The speed of exhaustion was measured by the "pellet method" used at the National Physical Laboratory, Teddington, England.[4] In all of the curves the speed of the pump in cc per second is plotted

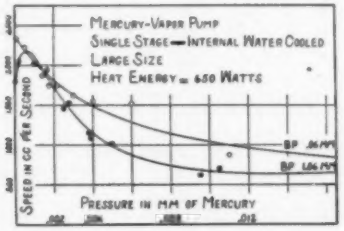

MERCURY-VAPOR PUMP
SINGLE STAGE — INTERNAL WATER COOLED
LARGE SIZE
HEAT ENERGY = 650 WATTS
SPEED IN CC PER SECOND
PRESSURE IN MM OF MERCURY

FIG. 6.

against the constant pressure maintained in the system at the instant the speed was determined. The type of pump and the conditions under which the data were taken are noted on each curve sheet. A sample of the data relative to a given pump (Fig. 4) is shown in Table 1.

The data plotted in Fig. 5 show the variation of speed with respect to pressure for an umbrella type (Fig. 1) pump for two differ-

[3] Definition introduced by Gaede.

[4] Kaye, High Vacua, Longmans, Green & Co., 1927.

ent backing pressures (*BP*). The curves show that the maximum speed attained recedes to lower values, and also towards lower pressures as the backing pressure increases.

The curves in Fig. 6 are for a particularly large throated, single stage, internal water cooled type, having an outside diameter of 60 mm, a nozzle diameter of 40 mm, and an annular jet area of 2.5

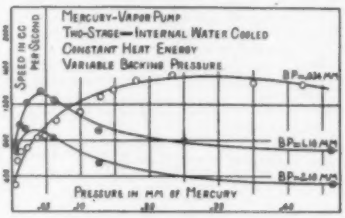


FIG. 7.

sq. cm. To reduce the air friction to a minimum the diameter of *B* was made 40 mm. The graphs show that this pump, at high degrees of exhaustion, worked at approximately equal speeds whether the backing pressure was .06 mm or 1.06 mm of mercury.

The curves in Fig. 7 are interesting. They represent the speed-pressure characteristics for a two-stage internal water cooled (40 mm outside diameter) pump, Fig. 3, with backing pressures of .034 mm,

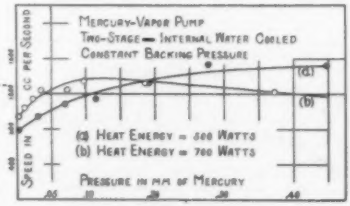

MERCURY-VAPOR PUMP
TWO-STAGE—INTERNAL WATER COOLED
CONSTANT BACKING PRESSURE
(a) HEAT ENERGY = 500 WATTS
(b) HEAT ENERGY = 700 WATTS
SPEED IN CC PER SECOND
PRESSURE IN MM OF MERCURY

FIG. 8.

1.10 mm, and 3.10 mm respectively. The general shape of the curves is the same as for the umbrella type (Fig. 5). Fig. 8 shows the effect of varying the heat energy supplied to this pump. Curve *a* is for an input of 500 watts, while curve *b* is for 700 watts.

The effect of ionization of the air pumped on speed came as a surprise. This study was made with a two-stage pump into which were fused electrodes E_1, E_2, and E_3 referred to earlier (Fig. 4). A Max Kohl

induction coil, with a series gap, supplying about 50,000 volts, was connected to the electrodes E_1 and E_3. The discharge thus passed along the entire path of the air as it was drawn from B by the action of the mercury vapor pump and out through A. In Fig. 9 the curve a

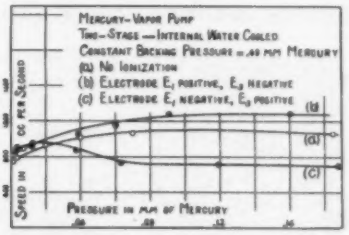


FIG. 9.

refers to the speed when the air pumped was *not* ionized (i.e., the normal speed); curve b the speed when the electrode E_1 was made positive and E_3 negative; while in curve c the polarity was reversed. Thus the *total change in speed due to ionization* of the air being pumped, when the pumping pressure was .1 mm of mercury or more, was as much as 90 per cent. The backing pressure in this instance was .49 mm of mercury. The curves shown in Fig. 10 are for (other conditions remaining constant) a backing pressure of .1 mm of mercury. Similarly in Fig. 11 for a backing pressure of .021 mm of mercury.

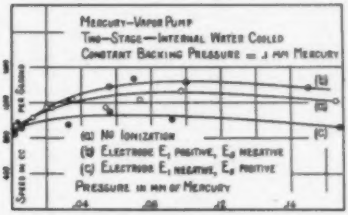


FIG. 10.

The mechanism of the phenomenon is a little obscure. The three sets of curves (Figs. 9-11) show that while the speed of this pump was markedly altered by ionization for pressures above .01 mm of mercury, there was little or no effect below that pressure. This suggests that the characteristics of the ordinary discharge play an important role.

Tentatively it may, in part, be explained thus,—when the discharge is *with* the flow of air through the pump, i.e., the electron flow opposed to it, the pumping action is slowed down since the negative ions under the action of the electric field, and to some extent to bombardment, are flowing against the stream of air. The positive ions being numerous only in the region in front of the cathode have, in comparison, but

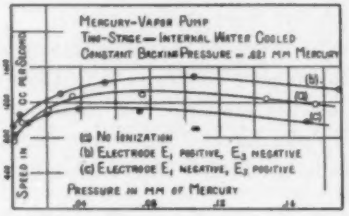

Mercury-Vapor Pump
Two-Stage — Internal Water Cooled
Constant Backing Pressure — .021 mm Mercury
Speed in cc per Second
(a) No Ionization
(b) Electrode E1 positive, E3 negative
(c) Electrode E1 negative, E3 positive
Pressure in mm of Mercury

FIG. 11.

little effect, the net result is a *slowing down* of the air stream. When the polarity is reversed so that the discharge is *opposed* to the flow of air the net result, for the same reason, is a *speeding up* of the air stream. The mobilities of the ions may have a minor effect, so also the mean free path of the ions; this latter, however, is conditioned on the degree of exhaustion. The above findings were also checked qualitatively by another and quite independent method.

LABORATORY OF PHYSICS,
UNIVERSITY OF ILLINOIS,
URBANA, ILL. JUNE 20, 1929.

A THERMOSTAT TO WORK OFF AC MAINS

By John Hume

This thermostat is described because of its convenience, reliability and ease of construction. Little claim is made for originality; rather it is a collection of the best features of various designs which have appeared in the literature from time to time.

The thermoregulator is shown diagrammatically in Fig. 1. Instead of the usual bulb the toluene container is in the form of a zig-zag or spiral tube. This has the advantage of exposing a large heating or cooling surface and reducing the lag of the thermoregulator behind temperature changes in the bath. The sensitivity of the regulator can

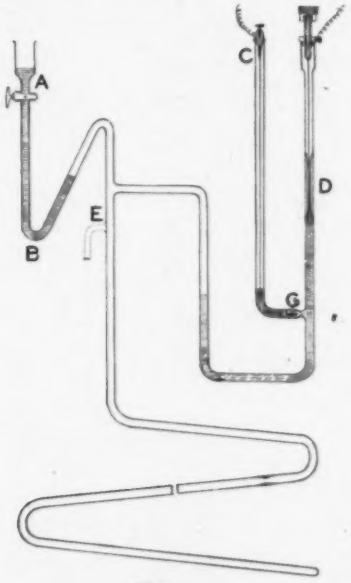


Fig.1

be increased as desired by joining on at *E* more zig-zag or spiral tubes. The capillary tube at *D* is 1.5 mm internal diameter, a size which has been found to be the best in practice. Down part of the length of the capillary extends a platinum wire soldered to the end of a brass screw passing through a threaded brass collar, which is fixed to the top of

tube *D* with a little sealing wax. The collar carries a terminal for attachment of a lead to the relay. The other wire from the relay is connected at *C*. A piece of platinum wire is sealed through the glass at *G* to make electrical contact between the mercury in the tubes *C* and *D*. A stop-cock is fitted at *A* for convenience in setting the regulator quickly to any temperature desired. The tube above the stop-cock should be as wide as is practicable. To prevent contact between the grease of the stop-cock and the toluene, a bend *B* is made in the tube and is filled with mercury—a device introduced by Mr. Whitaker of this department.—When the regulator is in its working position, the level of the mercury above the stop-cock *A* is adjusted so that the mercury in *D* just fails to make contact with the platinum wire. With this gap in the regulator, when the current is switched on, the heating element is activated. When the bath attains the required temperature, the cock *A* is shut, and almost immediately the mercury touches the platinum wire shorting the relay. Fine adjustment can be made by the brass screw at the top of the tube *D*. The temperature of the bath can be raised at any time by opening the cock and closing it again when the required temparature is reached. If a lower temperature is required, a rubber tube is connected to the mouth of the tube above *A*, and by blowing into this tube the mercury can be forced well up the platinum wire. The cock is then closed and when the bath has cooled sufficiently, opened and again closed.

A thoroughly reliable type of relay is shown in Fig. 2. *A* and *A'* are brass uprights each carrying a jewel hole of a clock. Running in the jewel holes is a spindle on which is mounted an arm *B*, made of light brass tubing. Fixed to the latter is a piece of very soft iron or "permalloy" above an electromagnet of 50 ohms resistance mounted on a wooden base. At the long end of the arm is an ebonite extension carrying an inverted U of copper wire. The ends of the wire dip into cups containing mercury. At the short end of the arm is a weight sufficient to keep that end down on the stop *D* when the magnet is not energised.

A simple heater, as made and used in the Department of Physical Chemistry in this University, can be constructed by coiling 9.14 meters of No. 32 S. W. G. nickel chromium wire into a spiral and threading it through 200 cm of glass tubing of 8 mm bore. The glass tubing is then bent into a U-shape to fit inside the bath in the most convenient way. Medicinal paraffin is then poured into the U-tube, filling each limb to within about 6 cm from the top. The resistance of the above length of wire is about 200 ohms, so that it is suitable for direct connec-

tion to the 200 volt mains, when approximately 1 ampere will flow.

The theoretical circuit is shown in Fig. 3. It will be seen that, if there is a gap between the platinum and the mercury in the regulator, the current in the resistance bulb circuit will pass through the relay

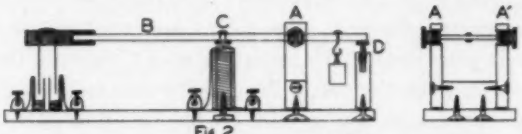


Fig. 2

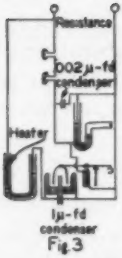


Fig. 3

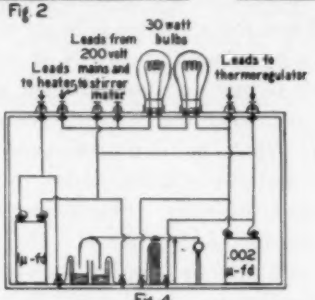


Fig. 4

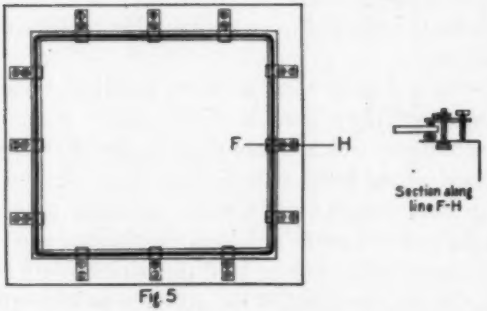


Fig. 5

and switch on the heater. If contact is made in the regulator the current will be shorted through the regulator and insufficient will pass through the electro magnet to hold down the arm, so that the heater will be switched off. This type of circuit cuts down sparking in the thermo-regulator to a very small amount; but further improvement can be effected by inserting a condenser of 0.002 μf capacity in parallel with the regulator. The result is that the platinum mercury make and break is perfectly satisfactory for months of continuous working. Sparking

in the mercury cups of the heating circuit is cut down by connecting a 1 μf condenser in parallel with them.

It is desirable to keep the relay and condenser in a dustproof box, on which the resistance lamps and terminals can be mounted. The wiring diagram of the box is shown in Fig. 4.

A thermostat of this description has been working night and day for about five months with a maximum variation of 0.001°. The bath contains about 150 liters of water and the zig-zag tube is about 7.5 mm internal diameter and contains, in two branches, 135 cc of toluene.

A convenient and easily constructed form of glass fronted bath has been devised by Mr. E. N. Warr, mechanic to this department. A rectangular piece is cut out of the side of a stout metal tank, leaving a rim about 7.5 cm broad—v Fig. 5—A piece of plate glass is obtained, 3.75 cm larger all round than the rectangle of metal removed. Holes are drilled in the metal rim, so that bolts passing through them will will just clear the edge of the glass, when it is laid symmetrically over the rectangular opening. Leather washers are fitted beneath the bolt heads, which are inside the tank (5 mm bolts are satisfactory). A piece of pressure tubing, through which is threaded a stiff copper wire is applied to the metal rim between its edge and the bolt holes, the copper wire being bent to keep the rubber tubing in the required shape. The ends of the rubber tubing are cut to fit closely together somwhere along the upper edge. The plate glass is laid on the rubber tubing and pressed down to form a water tight joint by small pieces of 4 mm thick brass, 4 cm long by 2 cm broad. These brass pieces are drilled in the center to be a sliding fit on the bolts mentioned above and are forced down by nuts threaded on the ends of the bolts. The outer ends of the brass pieces are drilled and tapped to take 5 mm cheese head screws, which bear on the metal of the tank and are adjusted to keep the brass pieces parallel to the surface of the glass. Little pads of leather are interposed between the glasspieces and the glass.

DEPARTMENT OF INORGANIC CHEMISTRY,
THE UNIVERSITY, LEEDS.
ENGLAND.

A SIMPLE AIR THERMOMETER

By J. E. Shrader

For several years the writer has recognized the need of some simple form of air thermometer to replace the rather clumsy and fragile form which has heretofore been on the market. The present form stands about five feet high and the glass part consists of a bulb connected by a capillary tube so bent as to allow for the insertion of the bulb into a steam boiler or a vessel of ice. There are several objections to this form. In the first place, as the thermometer is ordinarily used, a scale range of about thirty-five cm is all that is necessary so that the length of the instrument can easily be shortened to a length of about two feet. In the second place, the glass part is so fragile that when given into the hands of an unskilled student the chances for breakage is great when inserting the bulb into the steam or ice bath. In the third place, the inverted bulb, unless properly arranged, after use usually becomes partly filled with mercury, which is drawn over into it due to temperature changes.

The proposed form overcomes these objections. The scale is shortened so that the instrument stands about two feet high. The bulb is mounted inside a metal reservoir with the capillary stem extending downward through a rubber stopper through the bottom of the reservoir. In this manner the bulb is protected from breakage except in case of extreme carelessness and the mercury, which may be drawn into the bulb may be easily removed by the adjustment of the mercury columns alone. A stop-cock at the bottom of the reservoir serves for the attachment of a rubber tube through which steam from a hypsometer may be passed into the reservoir to bring the thermometer bulb to steam temperature. Pressure may be adjusted for constant volume by the motion of either the reservoir and bulb or the free end of the mercury tube which carries a glass extension of the same size capillary as that of the bulb.

When conditions have reached a steady state and observations have been made at steam temperature, crushed ice may be packed about the tube and observations made for zero temperature conditions. It is best to perform the operations in the order given so that at the end the ice may be allowed to melt and the water drawn off.

Usually it is instructive to perform an experiment at the same time with a constant pressure themometer. This may be easily done by

using a capillary tube closed at one end and having a certain quantity of air confined by a globule of mercury. An opening is provided in the top of the reservoir so that this tube may be inserted and the experiment performed simultaneously with the constant volume thermometer.

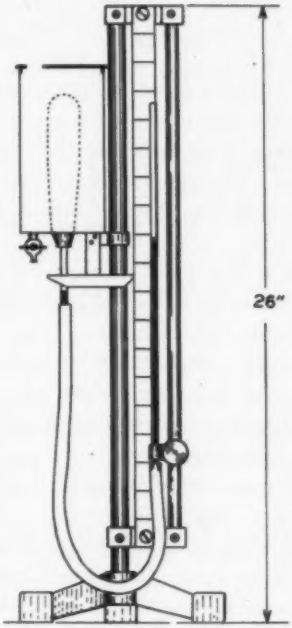


FIG. 1. *Diagram of air thermometer.*

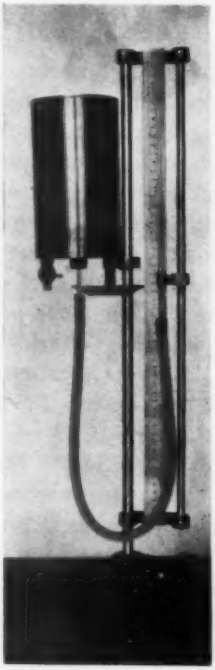


FIG. 2. *Photograph of air thermometer.*

Fig. 1, is a simple diagram of the simplified air thermometer. Fig. 2, is a photograph of the instrument which has been made and used in the laboratory of the writer. This form has proven very satisfactory and gives very good results.

DREXEL INSTITUTE, PHILADELPHIA.
JUNE 5, 1929.

A NON-POROUS ALUMINUM ALLOY FOR VACUUM CHAMBER CASTINGS

By Edgar C. Nichols

The development of aluminum alloys in the past few years has been greatly stimulated by airplane construction. These alloys are constantly finding new fields of usefulness. This is especially true in the design of scientific apparatus. Here an application for nearly every alloy of the aluminum family can be found.

In the construction of chambers for vacuum spectrographs, vacuum arcs, and similar apparatus, it has been customary to use plates of rolled metal of brass or steel. These plates were built into the required shape and soldered or welded together. This practice has been necessary because of the lack of a metal of sufficient strength which, when cast, was non-porous.

In searching for a non-porous metal which could be cast, an alloy, silicon aluminum, was tried. Silicon aluminum is a close grained alloy used for leak proof castings, gas tank fittings, et cetera. This alloy has proved to be remarkably non-porous, comparing favorably with glass in this respect. A test of the casting[1] described below was made in the laboratory of the Mount Wilson Observatory, Pasadena, California. The casting was six inches in diameter, six inches long, with three eight inch walls. Five-inch bosses with two-inch diameter holes were provided at each end for core prints. The bosses were machined fairly smooth and the holes covered with glass plates, waxed on. A hole was drilled and tapped in the side for a one-quarter inch exhaust tube and the screwed joint was carefully waxed. The chamber was warm from the waxing on of the glass plates when put on the pump, which was a Cenco Hyvac. There was some moisture inside which soon disappeared. The chamber was exhausted until the McLeod gauge gave a reading of .008 mm mercury, further pumping having no effect. The chamber was left in this condition and after a week's time practically no change had taken place.

Silicon aluminum is composed of five percent silicon and ninety-five percent aluminum. This alloy has an ultimate strength of approximately twenty thousand pounds per square inch with four and six tenth percent elongation and Brinell hardness test of forty. For

[1] J. E. Belanger, M. E., Aluminum Alloy Casting Co., 3132 Alosta St. Los Angeles, Calif.

sand castings, the metal should be poured at a temperature of one thousand two hundred fifty degrees Fahrenheit. The pouring temperature is very important. In melting, the gas fumes should be kept away from the molten metal as much as possible as the metal has a tendency to absorb these gasses and a defective casting, due to gas holes, may result. Silicon aluminum cannot be heat treated but an annealing at seven hundred fifty degrees Fahrenheit for four or five hours in dry electric heat followed by cooling in the open will give a closer grained material. This alloy may be welded successfully to sheet aluminum and resists the action of salt water.

In designing castings of silicon aluminum, sharp corners should be avoided, because of the possibility of cracks, by using fillets of at least twice the thickness of the metal. For machining, a lubricant of half lard oil and half kerosene should be kept flowing constantly on the work and the tool should have plenty of rake.

The vacuum test was made by Dr. Sinclair Smith.

DEPARTMENT OF INSTRUMENT DESIGN,
MOUNT WILSON OBSERVATORY,
PASADENA, CALIFORNIA.

Life and Work of Sir Norman Lockyer. By T. Mary Lockyer and Winifred L. Lockyer with the assistance of Prof. H. Dingle. xii+ 474 pp. Macmillan and Co., London, 1928.

The first twenty-six chapters of this splendid memoir constitute the general biography since they contain a survey of the career of Sir Norman Lockyer from the personal point of view, presenting a detailed record of the events of his life and scientific activities and showing how he appeared in the home circle or among his many friends. Professor Dingle has been largely responsible for the composition of these chapters.

"At the suggestion of Sir Richard Gregory, it was decided to supplement the general biography with contributions from leading authorities upon some fields of work in which Sir Norman was a pioneer, and the knowledge of which he advanced by original observations and conceptions." This happy idea is responsible for a number of important chapters from which the following deserve special mention. The Constitution of the Sun; The Dissociation Hypothesis; The Sun and Meteorology; The Meteoric Hypothesis and Stellar Evolution; all by H. Dingle. The Constitution of the Sun: A Modern View; by C. E. St. John. Dissociation Equilibrium; by M. Saha. Solar Physics in Relation to Meteorology; by Sir Napier Shaw. Sir Norman Lockyer's Work in the Light of present Astrophysical

Knowledge; by H. N. Russell. The Story of Helium; by Sir Norman Lockyer.

The volume as a whole is most inspiring and the contributions by the leading authorities in the special fields are very instructive. In the opinion of the writer of this short review every student of astrophysics who has not read this book not only owes it to himself as a duty to do so as soon as possible but also he still has in store an intellectual treat.

There is also an esthetic treat since the publishers have collaborated to the fullest extent with the authors in producing a very elegant volume The frontispiece is a very fine reproduction of a portrait of Sir Norman taken about 1904. There are two other portraits of the same subject corresponding to the years 1856 (about) and 1895. In addition to these three plates there are fourteen more representing observatories, spectrograms, etc. The paper and type are adapted especially for reading by aid of artificial sources of light.

H. S. UHLER